

Attachment "7"

(Part 1 of 2)

Further measurements and reassessment of the magnetic-monopole candidate

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Within the stack, consisting of 35 Lexan detectors and three nuclear emulsions, in which the unusual event was found, we have measured tracks of ~ 200 cosmic-ray nuclei with $26 \leq Z \leq 83$, which provide an internal calibration of the response of the detectors. Our measurements in Lexan and in emulsion together show that the unusual particle produced a knockon-electron energy distribution incompatible with any known nucleus. The track etch rate and its gradient in Lexan give the quantity $|Z|/\beta$ and, if the particle was a nucleus, a lower limit on its velocity. We found $|Z|/\beta \approx 114$ at each of 66 positions in the Lexan stack extending over a range of ~ 1.4 g/cm². The best fit to the Lexan data alone would be for a hypothetical superheavy element with $Z \approx 108$ to 114 and β such that $Z/\beta \approx 114$. A known nucleus with $90 \leq Z \leq 96$ would also give an acceptable fit to the Lexan data if it fragmented once in the stack with a loss of about 2 units of charge, keeping $Z/\beta \approx 114$. A nucleus with $Z < 90$ could maintain $Z/\beta \approx 114$ only by a properly spaced set of fragmentations. A nucleus with β as low as 0.6 could fit the Lexan data only if it fragmented at least eight times in succession, with a probability $\sim 10^{-17}$. In the 200- μ m G-5 emulsion, visual measurements of the track "cores" produced by relatively-low-energy electrons (≤ 10 keV) are consistent with the Lexan result that the unusual particle had $|Z|/\beta \approx 114$. However, measurements of the density of silver grains at radial distances greater than ~ 10 μ m show that the particle produced far fewer high-energy (≥ 50 keV) knockon electrons in each of the three emulsions than would a known nucleus with $Z/\beta = 114$. If it were a known, long-lived nucleus with $Z < 96$, and therefore having $0.84 \geq \beta > 0.6$ in order to fit the Lexan data, its signals in the three emulsions would imply a very low Z/β of only ~ 85 instead of 114. The abnormally small production rate of long-range electrons observed in all three emulsions is the essential evidence that we have found a unique particle. A monopole does not provide an acceptable fit to all of the data. A slow particle ($\beta \approx 0.4$) could fit all of the observations, provided its mass were so great ($> 10^3$ amu) that it did not slow appreciably in the 1.4-g/cm² stack. A fast ($0.7 \leq \beta \leq 0.9$) antinucleus with $Z/\beta \approx -114$, because of its low Mott cross section for production of high-energy knockon electrons, could fit the data, especially if it fragmented once with loss of 1 or 2 units of charge. An ultra-relativistic ($\beta \geq 0.99$) superheavy element with $Z \approx +110$ to $+114$ can also account for the data and is not in conflict with any negative searches. Our knowledge of the Z and β dependence of the response of Lexan appears sufficient to preclude values of $|Z|/\beta$ less than ~ 110 . An explanation of the weak distant energy deposition in terms of fluctuations by a normal nucleus or locally insensitive emulsion regions appears to be unlikely. Freak occurrences such as a 10^{20} -eV jet or an upward moving nucleus do not fit the data. Having achieved only an incomplete characterization of a single example of what appears to be a new particle, we emphasize the obvious—that further examples of such particles must be found before its identity can be established.

1. INTRODUCTION

In ten years of study of the ultraheavy cosmic rays—those with nuclear charge $Z \geq 70$ —one event out of several hundred of these rare particles has stood out as abnormal and quite possibly the first representative of a new class of heavily ionizing particles. In 1975 we mistakenly claimed¹ that the behavior of the particle as it passed through a stack of several types of visual detectors was compatible only with its being a monopole with magnetic charge $g = 137e$ and speed $\beta c \approx 0.5$ c.

In the numerous sheets of Lexan in the stack its ionization rate was very high and roughly constant. From experience with previous Lexan detectors we estimated $|Z|/\beta$ to be ~ 137 and $\beta \geq 0.9$ if it

were a nuclear particle. However, in a layer of nuclear emulsion it produced an anomalously small number of energetic δ rays such as would be produced by a particle with much lower Z/β . In a fast film supposedly sensitive to Čerenkov light from a heavily ionizing particle with $\beta \geq 0.68$, it produced only a small spot that we interpreted as the ionization from a particle of low velocity, $\beta < 0.68$.

Several errors in the original analysis, together with the publicity and scientific criticisms that followed, have discredited the experiment and obscured the fact that this particle did exhibit a peculiar behavior, outside of any reasonable statistical fluctuations associated with any particle yet seen in the cosmic radiation. We intend here to

give a detailed account of the experiment, to show that no previously discovered particle can account for the data, and to show that several hypothetical particles are compatible with the data.

The techniques for particle identification with Lexan detectors are well known and uncontroversial. They are thoroughly discussed in a monograph² but will be reviewed in Sec. IV for the convenience of the reader. Since the initial report of the monopole candidate¹ we have increased the number of Lexan data points from 58 to 66 for that event and have measured nearly 200 other events with $26 \leq Z \leq 83$ recorded in the same flight, allowing a relation between signal and Z/β to be established for each Lexan sheet. From this internal calibration we find that the average value of $|Z|/\beta$ should be ~ 114 rather than ~ 137 . Despite this embarrassing change in the value of $|Z|/\beta$, the qualitative claim that our particle was the most penetrating particle with such a high ionization seen to date remains unquestioned.

The techniques of track-structure measurement in emulsion developed by one of us (W.Z.O.) and used in the initial report¹ had not previously been published, and the interpretation of such measurements depends on the construction of a model of track structure that must be experimentally tested. Criticism³⁻⁶ of the initial paper was directed chiefly at our undocumented claim that the visual measurements of track structure in emulsion, together with a knowledge of Z/β from the Lexan, allowed the particle's velocity to be estimated at $\beta \approx 0.5$ with an absolute upper limit of $\beta = 0.6$. In Sec. VI of the present paper we take a different point of view that we believe experts on track structure in emulsion will regard as uncontroversial because our conclusion does not depend on the details of the track model used. Instead of claiming that we can measure the particle's velocity, we present several kinds of experimental evidence (visual measurements of two quantities denoted R_1 and R_2 , photographic evidence, and silver-grain densities measured with an automated microscopic-image dissector) that the energy deposited at large radial distances around the track of the monopole candidate was too low to be compatible with a known, long-lived nucleus with $Z \leq 96$, with $Z/\beta \approx 114$, and thus with $0.84 \geq \beta > 0.6$. In the initial paper the 200- μm Ilford G-5 emulsion was examined but the other emulsions were not studied. In the present work the claim of an abnormally low production of high-energy electrons is greatly strengthened by measurements in two independent 10- μm Kodak NTB-3 emulsions as well as in the 200- μm emulsion.

The fast film for recording Čerenkov light emitted by a single heavily ionizing particle is in prin-

ciple a valuable tool for determining whether the particle's velocity appreciably exceeds the threshold value given by $\beta_{\text{crit}} = n^{-1}$. The plastic radiator coupled to our fast film has a refractive index $n = 1.515$, so that $\beta_{\text{crit}} = 0.66$. Earlier experiments in which a few heavily ionizing particles were followed through a fast-film Čerenkov detector^{7,8} into a Lexan stack suggested that particles with $Z \geq 60$ and $\beta \geq 0.68$ would, in that particular film, produce a large region of developed silver grains attributable to the cone of Čerenkov light. Unfortunately, the film prepared by Eastman Kodak for the experiment in which the monopole candidate was found was less sensitive than the earlier film. By etching the plastic radiator above the fast film we have been able to observe, for each particle of interest, an etched track that serves to locate the center of the cluster of developed silver grains. This removes any ambiguity as to the correct spot associated with each event. Despite strenuous and ongoing efforts to relate the radial distribution of silver grains in these spots to the presence or absence of Čerenkov light, we have not been able to substantiate our earlier claim regarding the speed of the monopole candidate based on the fast film. In the present work we draw only upon measurements made in the Lexan detectors and in the nuclear emulsions.

II. HISTORY OF THE EXPERIMENT

Some time ago, two of us (W.Z.O. and P.B.P.) planned a series of balloon flights in which a stack of Lexan sheets and one or more layers of nuclear emulsion would be used to measure both the charges and velocities of the rare, ultraheavy cosmic rays. An important goal of the experiments was to test the idea of W.Z.O. that, over a useful range of velocities, $0.3 \leq \beta \leq 0.6$, measurements of the radial distribution of silver grains around a track in a single layer of emulsion could be used to estimate both Z and β without the need for Lexan or other detectors.

By the time of our first balloon flight the group included Shirk and Kobetich at Berkeley and Pinsky, Eandi, and Rushing at Houston. Pinsky⁸ had built a detector consisting of a layer of plastic radiator coated on both sides with a thin layer of Eastman Kodak's very high speed 2485 film that was to be used to study the possibility of imaging the Čerenkov light emitted by a single heavily ionizing nucleus with $\beta > \beta_{\text{crit}}$.

An 18-m² array containing a stack of Lexan sheets, a 200- μm emulsion layer, and the fast-film Čerenkov detector was launched from Minneapolis on September 4, 1970. Because of failures of the descent mechanisms, it became derelict,

but after a 15-day, 5500-mile journey, it landed of its own accord near Regina, Saskatchewan. It spent about 40 h at ~ 2.8 g/cm², ~ 20 h at ~ 5.5 g/cm², and the remainder of the 15 days at greater depths (largely unknown). The emulsion was dark from the long exposure but usable. About half of the Čerenkov detectors survived the hard landing. All of the emulsion was scanned twice at Houston in a stereomicroscope and visual measurements of the track structure parameters R_1 and R_2 (see Sec. VIB) were recorded for events thought to be heavier than Fe. The locations, zenith and azimuth angles, and values of R_1 and R_2 were sent to Berkeley, where the various sheets of Lexan were chemically etched in a systematic way to be discussed in Sec. IV. The Z and β determined with the Lexan were taken to be correct, and all events with $Z > 50$ were sought in the fast-film Čerenkov detectors. The charge and energy distributions determined with the Lexan detectors have been published.⁷ The analysis of the spots containing excess silver grains at the sites traversed by high- Z cosmic rays in the fast-film Čerenkov detectors has also been published.^{7,8} The measurements of track structure in the emulsions have never been published; they will be discussed in Sec. VI of the present paper.

Later the present authors constructed a 30-m² array shown in Fig. 1, but in three successive launch attempts, the balloons failed. After a six months' storage in Houston, the array was separated into a 10-m² and a 20-m² array and successfully launched at Sioux City, Iowa. The 10-m² stack was flown for 60 hours at ~ 3 g/cm² beginning September 18, 1973, and the 20-m² stack was flown for 60 hours at ~ 4.5 g/cm² beginning September 25, 1973. A shifting mechanism, used to distinguish events at float altitude from events during ascent, moved the top two Lexan sheets by about 2 cm during the earlier, abortive launches. They were left in a unique shifted position throughout the flights in September, 1973.

The Sioux City array differed in several significant respects from the Minneapolis array. (1) It contained two independent sets of Čerenkov radiator and fast film, each wrapped in light-tight paper. (2) The film, nominally designated as EK-2485, was different from that used in the Minneapolis flight. Eastman Kodak changed the composition so that a more convenient developer could be used, but unfortunately achieved a lower sensitivity than that of the Minneapolis film. (3) In addition to the 200- μ m Ilford G-5 emulsion commonly used by cosmic-ray experimenters, we included two 10- μ m Kodak NTB-3 emulsions on cellulose triacetate backing, each wrapped in light-tight paper. (4) The thickness of light-tight wrapping

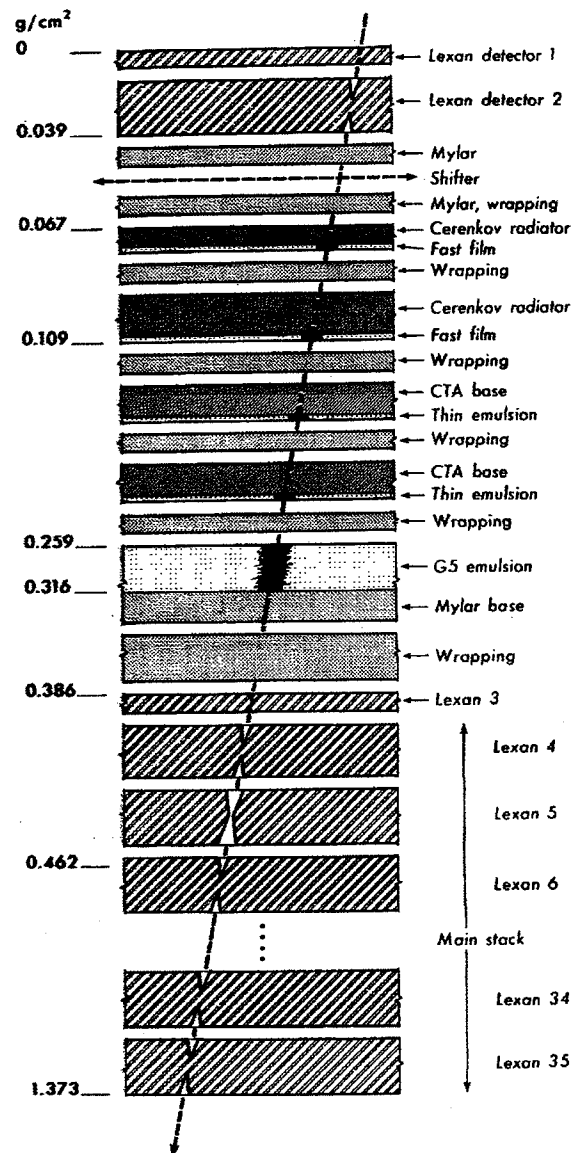


FIG. 1. Vertically expanded view of detector array with depths in g/cm² Lexan equivalent. The particle traversed the stack at a zenith angle of $\sim 10^\circ$. Details of the wrapping and of the shifting mechanism are not shown.

paper was less for the Sioux City flights than for the Minneapolis flight.

Figure 1 is a more detailed and accurate sketch of the constituents of the stack than was presented in the initial paper.¹ The thickness in g/cm² Lexan equivalent, measured normal to the stack, is indicated at several positions in Fig. 1. In the sketch in Ref. 1 the thickness of material between Lexan sheet 2 and Lexan sheet 3 was incorrectly labeled. It was taken to be 0.625 g/cm² in drawing

the figure in Ref. 1, whereas it should have been 0.347 g/cm^2 . The reader should note that an exploded view of a narrow column through the detector is shown in Fig. 1. The actual stack was $\sim 1 \text{ cm}$ thick and 30 m^2 in area.

The $200\text{-}\mu\text{m}$ Ilford emulsion was developed by H. H. Heckman's group at Lawrence Berkeley Laboratory during the period October 16 to November 2, 1973. The $10\text{-}\mu\text{m}$ Kodak emulsions were developed by the Johnson Spacecraft Center Photographic Technology Division at about the same time. The Lexan was etched in the spring of 1975, after a hiatus of about 18 months during which the Berkeley group analyzed a stack of Lexan exposed on the Skylab orbiting workshop.⁹

Scanners at Houston used stereomicroscopes to locate tracks in the $200\text{-}\mu\text{m}$ emulsion that appeared likely, because of the high density of δ rays, to have been produced by cosmic rays with $Z \geq 40$. A list of these tracks, with their locations, zenith and azimuth angles, and track structure parameters R_1 and R_2 , was sent to Berkeley, where the corresponding tracks in the Lexan sheets were to be located and measured. The track of the monopole candidate in the emulsion had not been recognized as unusual. About half of the 68 events later established by Lexan measurements to have $Z \geq 40$ were recorded as having larger halo radii, R_2 , than did the monopole candidate. The photomicrographs in Figs. 14 and 15 show that the monopole-candidate track had a lower density of high-energy δ rays than did a number of the other events. It was thus completely unexpected when a technician, Walter Wagner, found that the track etch rates in the Lexan sheets indicated that it was an extremely heavy, penetrating particle with apparently no change in ionization rate with depth.

The erroneous identification of this particle as a monopole came about as follows. In the analysis of the Minneapolis flight,⁷ the Skylab experiment,⁹ and balloon flights by another group,¹⁰ the Lexan stacks had had quite similar responses, with track etch rate v_T going as $\sim (Z/\beta)^\eta$, where η was always in the range 3.5 to 4. It was natural, then, in the preliminary analysis of the Sioux City flight to assume a similar response. Assuming the Sioux City Lexan stack to be identical to the Lexan used on the Skylab, we calculated that the monopole candidate had $Z/\beta \approx 137$ and did not change with depth. Having searched for monopoles in the past, we were well aware of the calculations of Cole and Bauer¹¹ showing that a monopole of strength g ionizes approximately at a constant rate, independent of β , given by replacing Ze by $g\beta$ in the Bethe-Bloch equation. With Dirac's quantization condition, $ge = n\hbar c/2$, one then expects the ionization rate of a fast monopole to look like that of a minimum ionizing nucle-

us with $Z = 137n/2$ and $\beta \approx 1$. The association of our particle with a monopole of strength $n = 2$ was obvious. From its weak signal in emulsion and an unpublished track structure model of Osborne, we inferred a low velocity, $\beta \approx 0.5$. Kinematics limits the maximum energy of δ rays to $w_{\max} = 2m_e c^2 \beta^2 \gamma^2$, which for $\beta \approx 0.5$ could, according to the model, account for the small value of the radius R_2 over which δ rays could be seen but would not affect the Lexan signal, which is produced dominantly by very low-energy electrons.

The remarkable coincidence of our estimate of the value of Z/β with the number 137 expected for a monopole, and our belief that the difference between this number and the charge of the heaviest nucleus previously seen in the cosmic rays, $Z = 96$, was far greater than estimated experimental errors, prompted us to publish the Letter¹ before doing the detailed calibrations of the Lexan, emulsion, and Čerenkov detector.

We soon communicated to many colleagues the results of our calibration of the Lexan, showing that Z/β was considerably lower than 137; independently several papers appeared, pointing out that a very heavy nucleus could, by one or more properly spaced fragmentations, maintain a roughly constant ionization rate and account for the observations, provided the emulsion evidence was disregarded.³⁻⁶ The critics were correct. Fragmenting nuclei can fit the Lexan etch-rate data, and the event is unique only if evidence for its anomalous nature can be substantiated in the emulsions or Čerenkov film.

Though it is not our purpose here to present a complete case history, we should explain why we did not retract our claim as soon as the Lexan calibration showed that Z/β was only ~ 114 instead of 137. The reason is that Ahlen pointed out¹² that the simple, first-order prescription, "replace Ze by $g\beta$ in the Bethe-Bloch equation," eliminates the β^{-2} factor but retains the logarithmic velocity dependence, which means that slow monopoles ionize less heavily than fast monopoles. The logarithmic contribution seems to have been overlooked until recently. Ahlen's detailed calculation, including the relativistic density effect, confirms the qualitative correctness of the simple prescription. For one specific model of track formation in a plastic detector—the restricted energy loss model¹²—Ahlen¹² showed that the slower the monopole, the lower the apparent Z of an electrically charged, minimum-ionizing particle with an equivalent signal. His calculations suggested that a slow monopole, if sufficiently massive to traverse the entire stack without significant decrease of velocity, might simulate a fast, electrically charged particle with $Z/\beta \approx 114$. Thus, our view in late 1975 was

that the particle was still compatible with a monopole if its velocity was indeed as low as we inferred from its weak signal in emulsion.¹³ In Sec. IV A, however, we will see that the restricted energy loss model does not give a good fit to available data for charged particles, and in Secs. VII B and VIII A we will conclude that a slow monopole is not a viable explanation of the event.

In 1976 two new developments made it clear that we could no longer claim that only a monopole could account for both the strong signal in Lexan and the weak signal in emulsion. First, R. Hagstrom, who had independently associated himself with the analysis of the emulsion data and was developing a quantitative model of track structure in emulsion, recognized that a heavy antinucleus, with $|Z| \geq 80$ and $Z/\beta \approx -114$, could fit both the Lexan and the emulsion data better than could its charge conjugate. Hagstrom realized that the abnormally low energy deposition at large radial distances could result from the smaller Mott cross section for scattering of electrons by a negative nucleus than by a positive nucleus. His explanation¹⁴ of the event remains a viable one. Second, given $|Z|/\beta \approx 114$ and the behavior of the Mott cross section, we recognized that an extremely relativistic ($\beta \approx 0.99$) superheavy nucleus, $Z \approx 110$ to 114, might fit both sets of data. Our view since then has been that the data are incompatible with a known, positive nucleus but that a monopole is not a good explanation.

III. KNOWN HEAVILY IONIZING PARTICLES IN THE COSMIC RAYS

The flux of ultraheavy cosmic rays is so low, $\lesssim 1 \text{ m}^{-2} \text{ day}^{-1}$, that they have so far been detected in the present-day cosmic radiation only with large arrays of plastic detectors and emulsions. Figure 2 shows the charge distribution of ultraheavy cosmic rays found in two recent experiments^{9,10} using Lexan detectors. Both distributions are roughly consistent with the histogram labeled " r -process abundances," which is the result of a typical calculation of the charge distribution expected if ultraheavy cosmic rays are accelerated from material synthesized by rapid neutron capture, then propagated through an exponential distribution of path lengths of interstellar gas (with characteristic length $\bar{\lambda} = 5 \text{ g/cm}^2$) during a time of $\sim 10^7$ years. The main points to note are the so-called "platinum peak" at $Z = 76$ to 78, the so-called "actinide gap" at $Z = 84$ to 89, the presence of a few long-lived actinides $Z = 90$ to 96, and the absence of any events with $Z > 100$. The resolution in these experiments was usually $\Delta Z \approx \pm 2$. Other experiments, including our Minneapolis flight,⁷ have

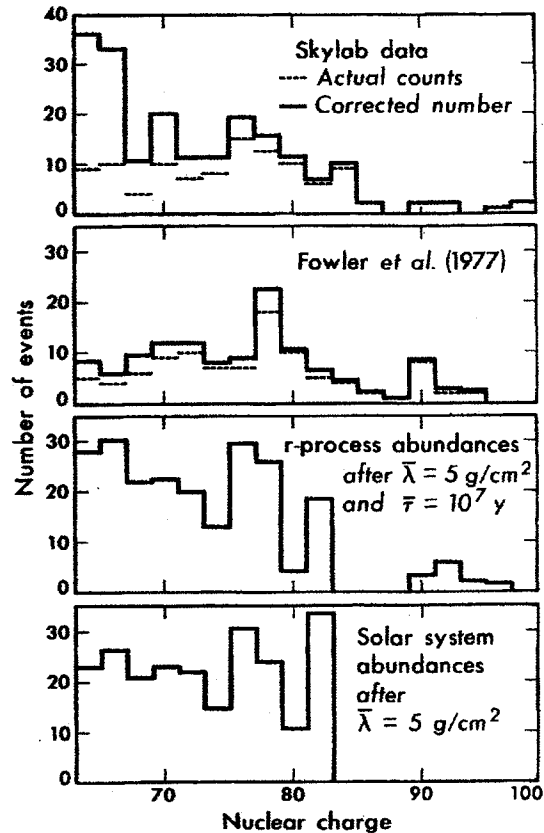


FIG. 2. Comparison of measured abundances of ultra-heavy cosmic rays with calculated abundances of material with r -process composition and with solar system composition, after distortion resulting from fragmentation and radioactive decay in interstellar space. Corrections to actual counts in top two histograms allow for detector efficiency (from Ref. 9).

given similar results but with poorer statistics. One can see from this distribution why a particle with apparent $Z/\beta \approx 137$ and apparent $\beta \approx 0.9$ would cause a stir. One can also see that a monopole with $n = 1$, which if relativistic would look like a minimum-ionizing nucleus with $Z = \frac{137}{2}$, would be hard to find because of the relatively large background of cosmic rays with $Z \sim 65$ to 70.

We will have occasion later to refer to the "iron peak." Because of its large binding energy per nucleon, there is a very pronounced abundance peak at $Z = 26$ which has been thoroughly studied with various cosmic-ray detectors. It is very convenient as an internal calibration to use this abundance peak in establishing the response of both Lexan and emulsion. Between $Z = 26$ and 32 the abundances of cosmic rays decrease by several orders of magnitude and thereafter decline erratically and less rapidly. The abundance ratio of ele-

ments with $Z \geq 65$ to iron is $\sim 10^{-5}$ (Ref. 9).

It is useful to list here the area-time factor accumulated in all the ultraheavy cosmic-ray experiments. Particles with magnetic rigidity greater than 14.7 GV can penetrate the earth's field at any latitude. The area-time factor for such particles was $1.67 \text{ m}^2\text{yr}$ exclusive of the Sioux City flights and increases to $1.88 \text{ m}^2\text{yr}$ when the Sioux City flights are included. For particles with magnetic rigidity such that they just penetrate the earth's field (and possibly overlying air) at the latitude of South Dakota or Minnesota where many balloon exposures are made, the area-time factor was $0.56 \text{ m}^2\text{yr}$ exclusive of the Sioux City experiment and increases to $0.77 \text{ m}^2\text{yr}$ when the Sioux City experiment is included. It is also useful to list the effective area-time factor, which contains the additional factor $\exp(-x/\lambda)$, where λ is the interaction length of the particle sought and x is the average thickness of overlying material. In a search for a superheavy nucleus, which would have a rather short interaction length, the effective area-time factors are $\sim 1.2 \text{ m}^2\text{yr}$ for high-rigidity nuclei and $\sim 0.36 \text{ m}^2\text{yr}$ for low-rigidity nuclei when all experiments are considered.

IV. ANALYSIS OF THE LEXAN DETECTORS

For the benefit of the reader who is not interested in the details, we state the results of the analysis of the Lexan data here.

Assuming that the particle was a known or hypothetical nucleus with charge to mass ratio given by the β -stability line, the best fit to the Lexan data is for $\beta \geq 0.95$, $Z \geq 108$, and average $Z/\beta \approx 114$; a good fit is also obtained for $\beta \approx 0.8$ to 0.84 , corresponding to $Z = 92$ to 96 , provided it fragments once with loss of 1 or 2 units of charge; with lower β more fragmentations are required to give an acceptable fit; for β as low as 0.6 the number of fragmentations required becomes at least 8, with an overall probability of $\sim 10^{-17}$. The critics³⁻⁴ of the original paper¹ accepted the fact that the Lexan data excluded any nucleus with β lower than ~ 0.6 to 0.65 . Later we will see that this completely noncontroversial result is all that is required of the Lexan data to show that the emulsion data are incompatible with any known nucleus.

A. Response of Lexan to heavily ionizing particles

When a heavily ionizing particle passes through Lexan or some other nuclear track-recording solid,² it can produce a latent, microscopic track of chemically reactive material a few tens of angstroms in diameter that can be enlarged to visible size by using a chemical reagent that preferentially attacks the reactive material. The shape of the

etch pit is conical, with cone half-angle equal to $\arcsin(V_c/V)$, where V_c is the general rate of etching of unirradiated material and V is the rate of etching along the particle trajectory. If the particle passes through a Lexan sheet an etch pit may be produced at both surfaces.

Etching at a rate greater than V_c occurs only where the energy deposited per unit volume exceeds some very high value. The radius of the region of enhanced etching has been determined² directly by electron microscopy and indirectly by electrolytic conductance measurements to be $\leq 10^{-6} \text{ cm}$. The track etch rate V is an increasing function of the energy density in this narrow region, and particle identification relies upon measuring V and determining how V depends upon Z and β of the particle.

Track-etch detectors such as Lexan are quite different from other detectors in that they are completely insensitive to energy deposited at distances larger than $\sim 10^{-6} \text{ cm}$. This has two important consequences, which can be easily understood by recalling that the cross section for knockon-electron production falls off rapidly with energy (e.g., as E^{-2} for close collisions): (1) The resolution is immune to fluctuations in the small number of high-energy knockon electrons, which deposit almost all of their energy outside of this region. (2) The etch rate V is related to the production rate of the very numerous electrons of very low energy ($\leq 1 \text{ keV}$) resulting from collisions at large impact parameters ($\geq 10^{-9} \text{ cm}$). These electrons have a small c.m. scattering angle, a small momentum transfer, and a scattering cross section given, in the approximation that they are unbound, by the simple Rutherford formula, which is exactly proportional to Z^2 . Thus V will be a function of Z^2 , independent of the sign of the charge. For these collisions at large impact parameter, an incompletely stripped nucleus would interact as if it had an effective charge Z^* less than its nuclear charge. In all experiments to date the following expression,¹⁵ based on measurements at energies below $\sim 10 \text{ MeV/nucleon}$, has been assumed to hold up to relativistic energies:

$$Z^* = Z [1 - \exp(-130\beta/Z^{2/3})]. \quad (1)$$

For $\beta \geq 0.6$ this expression predicts $Z - Z^* \leq 2$. Fowler *et al.*¹⁶ have shown that theoretical cross sections for radiative and nonradiative electron attachment and stripping lead to a qualitatively similar conclusion.

The dependence of the energy density deposited at very small radial distances on the velocity of the incoming particle is complicated. One must take into account the energy deposited both by the primary excitation and by the secondary excitation

from knockon electrons.¹⁷ No theoretical expression for the dependence of etch rate on Z and β has been derived. Instead, one assumes that etch rate is a function of the appropriate expression for energy density at small radial distances. A power law relating etch rate to energy density at small radial distances gives an excellent fit to data covering a wide range of etch rates. Several expressions for energy density at small radial distances have been used:

(1) Benton¹⁸ and others¹⁹ have assumed that the energy density at small radial distances can be approximated by the restricted energy loss, defined as the energy lost in collisions leading to electrons with kinetic energy less than w_0 , where w_0 is taken empirically to give the best fit to the data. From studies of ions with $Z \leq 26$ and $\beta \leq 0.2$, Benton and

co-workers chose $w_0 \approx 350$ eV. The restricted energy loss is given by

$$(dE/dx)_{w_0} = (2\pi N_e e^4 Z^2 / mc^2 \beta^2) \times [\ln(w_{\max} w_0 / I_{\text{adj}}^2) - \beta^2 - \delta(\beta)], \quad (2)$$

where N_e = number of electrons/cm³ in the detector, $w_{\max} = 2m_e c^2 \beta^2 \gamma^2$ is the maximum electron kinetic energy set by kinematics, I_{adj} is an adjusted mean ionization potential of the detector, and $\delta(\beta)$ is a parameter that takes into account the reduction in ionization rate due to the polarization of the medium at relativistic velocity. This parameter is zero for $\beta \leq 0.8$ but represents a significant correction term at greater velocity, nullifying most of the relativistic rise due to the logarithmic term. In what follows we use the expressions of Sternheimer²⁰ for $\delta(\beta)$ in a plastic,

$$\delta = \begin{cases} 0, & \text{for } x < 0.14 \\ \ln(\beta^2 \gamma^2) - 3.21 + 0.456(2.0 - x)^{2.78}, & \text{for } 0.14 \leq x \leq 2 \\ \ln(\beta^2 \gamma^2) - 3.21, & \text{for } x > 2 \end{cases} \quad (3)$$

where $x = 0.5 \log_{10} e \ln(\beta^2 \gamma^2)$. To our knowledge, Eq. (2) has been used only for $Z \leq 26$ and $\beta \leq 0.2$, and no attempt has been made by those who use it to determine whether the data can be fitted better with some other expression.

(2) Price and co-workers,²¹⁻²⁴ in some of their early studies of cosmic rays with Z up to ~ 96 and β up to ~ 1 , rejected the restricted energy loss model as severely underestimating the charges of ultraheavy nuclei at high velocities, and chose a semiempirical expression of the form

$$J(K) \propto (Z^2 / \beta^2) [\ln(\beta^2 \gamma^2) + K - \beta^2 - \delta(\beta)], \quad (4)$$

where K is a parameter chosen to give the best fit to both accelerator data and to abundance peaks in the cosmic rays at Fe ($Z=26$) and at the r -process peak at $Z=76$ to 78. In the case of Lexan, for which $w_0 = 350$ eV and $I_{\text{adj}} = 69.5$ eV, the terms in square brackets in Eqs. (2) and (4) would become equal if K were chosen to be 11.2, so that the two expressions would then have the same dependence on Z and β . To fit data at high Z and β , it was found necessary to assign a much larger value to K . In their analysis of Ne, Si, Ar, and Ti ions from the Berkeley Hilac and six ultraheavy cosmic rays detected in a 10.2-g/cm² stack consisting of 120 Lexan sheets, 9 layers of Ilford G-5 emulsion, and 56 layers of steel absorbers, flown at Sioux Falls, South Dakota, O'Sullivan *et al.*^{21,22} found that Eq. (4) with $K \approx 62$ gave the best fit to the data.

(3) In the most recent cosmic-ray experiments Shirk *et al.*^{7,9} and Fowler *et al.*¹⁰ found that the best value of K was sufficiently high as to make the

logarithmic dependence negligibly small, and they used the simple expression

$$J(K=\infty) \propto (Z^2 / \beta^2). \quad (5)$$

Table I summarizes the data used to choose among the three models for energy density at small radial distances, Eqs. (2), (4), and (5). The method is to compare, in the same Lexan stack, the track etch rates for nuclei of the well-defined Fe peak with etch rates for "standard" nuclei, whose identities have been independently established. The first group of standard particles, from the Berkeley Hilac, had precisely known values of Z and β . The second group had their charges determined, with a fractional standard deviation of $\sim 4\%$, by photodensitometric measurements of their tracks in nine layers of Ilford G-5 emulsion.²¹ The use of emulsion to identify ultraheavy cosmic rays, and the model of track formation in emulsion, are discussed in Ref. 16. One of these particles was particularly valuable as a test of the three models because it penetrated the 10.2-g/cm² stack of emulsions, Lexan, and steel with no perceptible increase in ionization rate,²² and its velocity was determined to be $\beta > 0.97$ (95% confidence), a value sufficiently high to lead to significantly different charges predicted by the three models. The third group consisted of 57 events with $70 \leq Z \leq 96$ and $\beta > 0.9$ detected in a Lexan stack⁹ flown on Skylab; the fourth group consisted of 58 events with $70 \leq Z \leq 96$ and $\beta > 0.88$ detected in Lexan stacks¹⁰ flown in several balloon flights. Both groups show a strong abundance peak close

TABLE I. Tests of various models of tracks in Lexan, using standard particles.

Source	Standard particle			Fe nuclei with same etch rate as standard particle		Z from Z^*/β model	Z from $J(K=62)$ model	Z from $(dE/dx)_{Fe}$ model
	Z	β	Z^*/β	β_{Fe}	$(Z^*/\beta)_{Fe}$			
Accelerator (Refs. 2 and 21)	10	0.149	66.1	0.39	66.5	10.0	10.2	11.0
	14	0.124	105.9	0.24	104.5	13.8	14.0	14.6
	14	0.149	90.6	0.295	87.0	13.4	13.6	14.3
	18	0.149	113.6	0.22	113.2	17.9	18.0	18.5
	22	0.149	135.1	0.18	134.4	21.9	22.0	22.2
Lexan/emulsion stack on Sioux Falls flight (Refs. 21 and 22)	~39	0.60	~65	0.38	68	41	40	39
	~44	0.60	~73	0.35	74	44	44	41
	~50	0.69	~72	0.34	76	53	52	49
	~70	0.78	~90	0.27	94	73	71	64
	~76	> 0.97	~77	0.32	80	80	78	67
	~92	0.65	~139	0.17	143	94	92	81
Lexan on Skylab (Ref. 9)	peak at $Z=77$ (57 events)	> 0.90 ($\bar{\beta}=0.95$)	~81	~0.32	~82	peak at 78	peak at 76	peak at 67
Lexan on other balloon experiments (Ref. 10)	peak at $Z=77$ (58 events)	> 0.88 ($\bar{\beta}\approx 0.93$)	~83	~0.31	~84	peak at 78	peak at 76	peak at 67
Monopole candidate, if a nucleus	?	≈ 1.0	?	0.22	114	114	109	89
	?	≈ 0.98	?	0.22	114	112	108	90

to the expected position of the "platinum peak" at $Z=76$ to 78, a weaker peak attributed to U and Th, and an absence of events at the expected position of the "actinide gap." The evidence from these two groups of data, though dependent upon astrophysical arguments (elucidated in more detail in Ref. 9), is valuable because it tests the three models at high β .

For each standard particle, of given Z and β , we find the velocity, and thus Z^*/β , for the Fe nucleus that gives the same etch rate as does the standard particle. Data for the standard particles are given in columns 1 to 4; data for the Fe nuclei are given in columns 5 and 6. We then use Eqs. (2), (4), and (5), together with the velocities of the Fe and of the standard particle and Z^*/β of the Fe, to calculate Z of the standard particle as predicted by each of the three models. The results are given in columns 7 to 9. Clearly the restricted energy loss model is inferior to the other two models, the discrepancy between the calculated Z and the "known" Z increasing as $|Z-26|$ increases. At low Z , the calculated charge is too high, by 10% at $Z=10$. At high Z the calculated charge is too low; for $Z\approx 76$ to 92 the error is about 10 charges. The information in Table I does not permit a choice to be made between the Z^*/β^2 model and the model of Eq. (4), with $K\approx 62$. For simplicity,

in recent balloon experiments and in this paper, the following expression is assumed to provide a satisfactory fit to data for $Z\geq 10$ and $0.1\leq\beta\leq 1.0$:

$$V(\beta, Z) = (Z^*/\xi\beta)^\eta, \quad (6)$$

where the free parameters ξ and η characterize the batch of Lexan and the etching treatment. This equation has been observed to hold over a range of $\sim 10^3$ in V for ultraheavy cosmic rays.²¹

Clearly it would be desirable to test the models of track formation in Lexan with particles of precisely known Z and β extending up to $Z=92$ and $\beta\geq 0.99$, instead of having to depend upon astrophysical arguments and upon charge identification in Lexan. In about 1980 it is expected that the Lawrence Berkeley Laboratory Bevalac will produce beams of nuclei with $\beta\approx 0.92$ and $Z\geq 82$, which will provide a more direct test. We believe the case against a restricted-energy-loss model, summarized in Table I, is quite strong. There is no known way by which the cosmic rays could show an abundance peak at $Z\approx 67$. The abundance patterns of both the cosmic rays and the elements that make up our solar system reflect their thermonuclear origin. Essentially all the elements beyond the Fe peak are made by either slow or rapid neutron capture. The s process leads to peaks at $Z=56$ and 82; the r process leads to

peaks at $Z=52$ and $76-78$. The two sets of peaks at $52-56$ and at $76-82$ correspond to nuclides with closed neutron shells, $N=82$ and 126 . The rare earths, including $Z=67$, form an abundance valley between these sets of peaks.

A final argument for the absence of a significant logarithmic rise in track etch rate is that in all velocity intervals studied, from $0 < \beta < 0.6$ to $0.9 < \beta < 1.0$, not only the position of the r -process peak but also the end point of the charge spectrum, at $Z \approx 96$, are correctly located when Eq. (4) or (5) is used for the close energy deposition.

We will return to this discussion in Sec. VIII, when we consider whether the monopole candidate could have been a normal nucleus with $\beta \approx 1$ that was misidentified in Lexan because the wrong β dependence was used in Eq. (6). Then we will discuss the last two rows of Table I.

B. Processing and calibration of Lexan from the Sioux City flights

The 30-m^2 Lexan stack consisted of 296 modules each $30.5\text{ cm} \times 30.5\text{ cm}$. The problem faced in processing a stack containing many tracks of particles with a wide range of ionization rates is to try to optimize the etching times of different portions of the stack so that each pair of etch pits associated with a track segment in a sheet is long enough for a measurement of its length with small fractional error to be made but not so long that the pits touch and form a cylindrical hole. We did the processing in three stages: (1) We etched layers 5 and 12 (see Fig. 1) for each module for a very long time (160 hours in the standard solution to be described below) so that etch pits at locations corresponding to the ultraheavy cosmic-ray events previously located in the emulsion could easily be seen in a stereomicroscope. (2) We set aside the thin Lexan sheets 1 and 3, and from the remaining sheets in the stack we cut out $5\text{ cm} \times 5\text{ cm}$ portions of Lexan centered on the trajectories of the particles located in sheets 5 and 12. For each event we etched the $5\text{ cm} \times 5\text{ cm}$ portion from every fourth sheet for a time that we estimated would give long but not touching etch pits, judging from the appearance of the pits in sheets 5 and 12. We measured the etch pit lengths in these sheets and constructed curves of track-etch rate V as a function of range R for each particle, from which refined etch times for the remaining $\frac{3}{4}$ of the stack could be determined. (3) We etched the remaining $5\text{ cm} \times 5\text{ cm}$ portions for optimized times and used the (V, R) data to calculate Z and β of the particles. In practice the etching times were limited to the values 1, 2, 4, 6, 10, 15, 20, 30, 48, 60, 80, and 160 hours.

As in the past, the etching was done under highly

reproducible conditions in polyethylene tanks containing 6.25 normal sodium hydroxide solution titrated by the supplier and specified free of sodium carbonate. To this was added 0.1% Dowfax surfactant. The tank was covered tightly to minimize evaporation, stirred, and held at $40.00 \pm 0.01^\circ\text{C}$. The dissolved products of Lexan are themselves a surfactant; to standardize the etching conditions,²⁵ blank Lexan sheets were etched in a fresh solution until a whitish precipitate first appeared. This solution was then used to etch Lexan sheets from the actual flight. The same solution was used until the concentration of etch products reached $\sim 1\text{ g/l}$; then a fresh solution was prepared. If a solution is used for too long, the general surface etch rate of the Lexan, as well as V , may increase.²⁵ To reduce the danger of possible systematic differences between calibration samples and samples containing events of interest, as many sheets as possible were etched at the same time in the same etching solution.

About 600 events were recorded by scanners at Houston as possibly having $Z \geq 40$. Of these, about 70% were found from observations in Lexan to have $Z \approx 26$. These all had small zenith angles. Nearly vertical tracks in emulsion look darker than shallow tracks and tend to have their charge overestimated in scanning. Of the remaining events, some passed out of the edge of a module at some point along their trajectory, some could not be found in sheets 5 and 12 because they came to rest before reaching sheet 5 (as was confirmed by etching sheets 1 or 4), and some could not be found because they penetrated the entire stack at Z^*/β too small to produce a visible etch pit. Because surface is etched away at a finite rate, $V_c \approx 0.16\text{ }\mu\text{m/h}$, the normal component $V \sec \theta$ must exceed V_c in order for an etch pit to be formed (θ is the zenith angle). For a vertically incident particle, in principle, the minimum detectable Z^*/β was ~ 65 for the Sioux City Lexan; for a particle at $\theta = 60^\circ$ the minimum detectable Z^*/β was ~ 74 .

Sixty-seven events with $Z \geq 40$ and the monopole candidate were studied in detail and will be described in this paper.

Figure 3 shows smoothed curves of etch rate as a function of distance along the trajectory in the main Lexan stack comprising sheets 4 to 35. Measurement techniques have been thoroughly discussed elsewhere.^{2,9} Several events with initial etch rates greater than $6\text{ }\mu\text{m/h}$, corresponding to slow, very heavy nuclei, were studied; they are off-scale above the top of this graph. Because etch rate is an increasing function of ionization rate, the curves in Fig. 3 are somewhat like Bragg curves. The data for the monopole candidate occur at an approximately constant etch rate of $\sim 2.9\text{ }\mu\text{m/}$

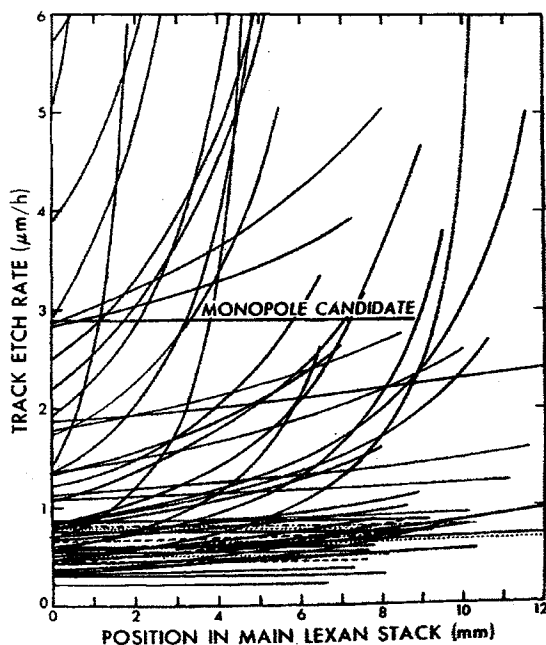


FIG. 3. Smoothed response curves for the majority of the ultraheavy particles found on the Sioux City balloon flights. A few slow particles with very steep curves are not plotted.

h, far above the other horizontal lines between ~ 0.3 and $\sim 0.8 \mu\text{m/h}$ that correspond to minimum-ionizing nuclei with Z up to ~ 83 that were detected on the flights. Only particles with steeply rising etch-rate curves, corresponding to slowing nuclei of lower velocity, reached etch rates as high as $2.9 \mu\text{m/h}$. In none of the experiments prior to the Sioux City flights had events been seen with constant etch rates greater than $1 \mu\text{m/h}$. To the experienced observer, the curve for the monopole candidate would excite considerable interest.

Module 104 contained the monopole-candidate event. Within 10 cm of its trajectory were one event with $Z=35$ and $\sim 10^2$ tracks of nuclei with $Z \approx 26$ that were used to calibrate the response of the individual sheets in that module. It was obvious from the appearance of the pits at the monopole-candidate track in sheets 5 and 12 that V was very high, so the $5 \text{ cm} \times 5 \text{ cm}$ portions of every fourth sheet were etched for only 20 hours. Measurements of etch pits in these portions are labeled as triangles in Fig. 4. We will discuss the determination of errors later. Most of the remaining three-quarters of the cut portions for the monopole candidate were etched for 30 hours in a fresh tank (along with cut portions for other events and larger portions of module 104 in which Fe calibration tracks were to be measured). The data for the 30-

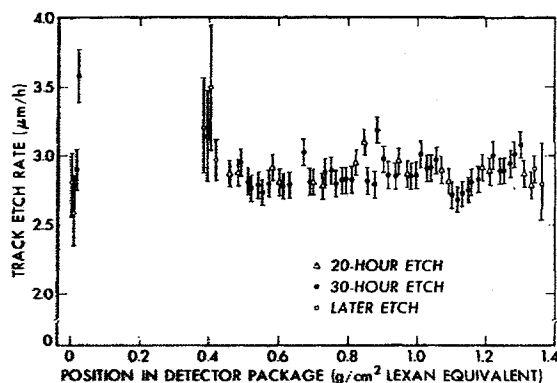


FIG. 4. Calibrated Lexan data for the monopole candidate.

hour etch are shown as solid points in Fig. 4. Recognizing that we had found a unique particle, we stored the cut portions of sheets 1, 3, 4, and 35 in the event that a better processing scheme might be developed at a future date. After the criticisms of the monopole paper were made public, it was decided to etch these four sheets. In a fresh solution sheets 1 and 3 (thickness $75 \mu\text{m}$) were etched eight hours and sheets 4 and 35 (thickness $250 \mu\text{m}$, same as for sheets 2 and 5 to 34) were etched 30 hours. Etch rates for these sheets are shown as open circles in Fig. 4.

Results of the calibration of the stack are shown in Figs. 5, 6, and 7. Etch pits corresponding to (V, R) points to the right of the scanning cutoff line in Fig. 5 were located in module 104 with a stereomicroscope and measurements of (V, R) were made with a Leitz Ortholux microscope.^{2,9} (The identification of the line in Fig. 5 with the position of Fe has recently been verified in a combination electronic + Lexan experiment in which a portion of this same batch of Lexan was used together with electronic detectors to resolve Fe isotopes in cosmic rays.⁸⁰) The data for the 30-hour etch are shown in Fig. 5 in a form simplified for legibility. The actual data for each event with $Z \approx 26$ consist of ~ 6 to 12 values of (V, R) lying along an approximately straight line of well-defined slope on the log-log plot. No attempt was made in Fig. 5 to identify each event with a separate symbol; closely spaced points were replaced by symbols indicating the number of points in that small area. The line labeled "curve adopted for Fe" follows the maximum in the distribution and has a slope accurately determined by the alignment of data points for individual events. The precipitous decline in population of points to the right of the line reflects the drop in abundance for $Z > 26$. The decline to the left of the line is less spectacular because of the presence of some elements with $Z < 26$. From the

1392

PRICE, SHIRK, OSBORNE, AND PINSKY

18

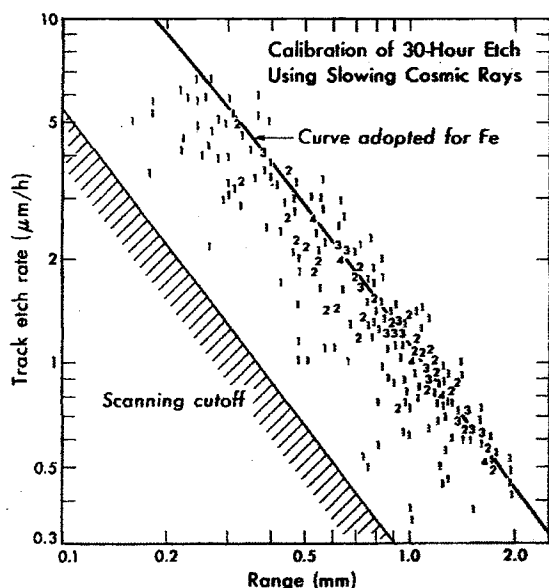


FIG. 5. Determination of the response to slowing Fe nuclei of the sheets etched 30 hours in Lexan module 104, which contained the monopole candidate.

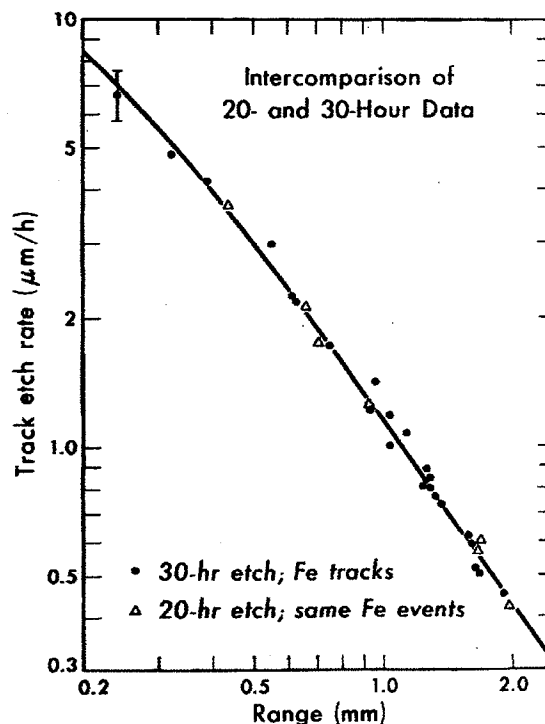


FIG. 7. Evidence that the responses of the sheets etched 20 hours and of the sheets etched 30 hours were the same (see text).

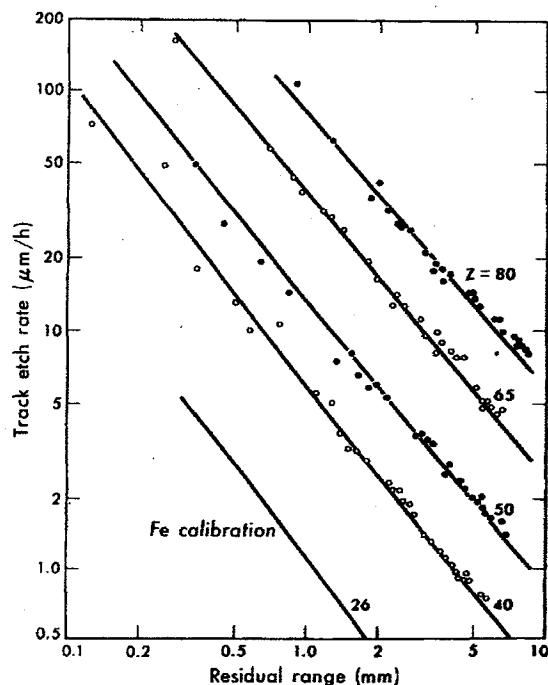


FIG. 6. Etch-rate response curves of several stopping ultraheavy nuclei as a function of residual range, along with the curve for Fe from Fig. 5. The parameters in the power-law response, Eq. (6), were determined from a fit to these data. Note that the curves of Fig. 3 become nearly straight when plotted on a log-log scale with residual range as abscissa.

position of the Fe line and use of the range-energy tables of Henke and Benton,²⁶ we determined the constants ζ and η in Eq. (6). The result of the calibration for the 30-hour etch is

$$V = (Z^*/92.3\beta)^{5.07} \mu\text{m/h}, \quad (7)$$

where the (coupled) standard deviations in ζ and η are 1.00 and 0.15, respectively. Data for events with $Z \geq 40$ that came to rest in the stack, shown in Fig. 6, extended to very high etch rate and provided support for the value $\eta = 5.07 \pm 0.15$ obtained with the Fe data. Note that this value for η is much higher than found for previous batches of Lexan. The batch used on the Sioux City flights differed from previous batches in that it did not have the trace of stabilizer normally added by the manufacturer to retard degradation by ultraviolet light.

Inserting the value $2.86 \pm 0.10 \mu\text{m/h}$ for the average etch rate for the monopole candidate, based on both the 20-hour etch and the 30-hour etch, gives an average value of $Z^*/\beta = 113.6 \pm 0.8$. Taking into account errors in ζ and η increases the error in average Z^*/β to ± 1.5 charges. In the remainder of this paper, for convenience we will usually use the rounded average value

$$Z^*/\beta = 114.$$

This determination of Z^*/β does not depend on the assumption of a power-law dependence of V on the energy deposition at small radial distances, because we are not extrapolating out of the range of etch rates measured for slowing Fe nuclei. It does, however, depend on our having chosen Eq. (5) instead of Eq. (2) or (4) for the energy deposition at small radial distances. If we had used Eq. (4), with $K=62$, the value of Z^*/β for the monopole candidate would depend slightly on its velocity through the terms in square brackets in Eq. (4). The discrepancy with the result from Eq. (5) is greatest for the highest velocity. For $\beta=1$, the value of Z^*/β drops from 114 to 109.3. If we had used the restricted-energy-loss model, Eq. (2), at $\beta=1$ the value of Z^*/β would have dropped to 90. From the evidence summarized in Table I, we rejected Eq. (2) but accepted either Eq. (4) or Eq. (5) as an adequate representation of the charge and velocity dependence of track formation in Lexan. Thus, we accept values of Z^*/β from ~ 109 to ~ 114 , depending on the particle's velocity.

To determine whether the data from the 20-hour etch and from the 30-hour etch of the cut portions for the monopole candidate could be treated as statistically equivalent, we made an intercomparison of Fe data, shown in Fig. 7. We traced five Fe events through cut portions etched 20 and 30 hours. These all passed within ~ 2 cm of the monopole candidate. The line is the fit for Eq. (7) which was derived for 30-hour data. The constant ξ in Eq. (6) was varied so as to minimize the square error for the 20-hour data alone. The best value for the 20-hour data agrees to within 2.5% with that for the 30-hour data. Thus, from Fe track measurements there appears to be no significant difference in the etching treatment or sensitivity of the sheets etched for 20 and for 30 hours. For the monopole candidate the average etch rate for the 20-hour data is $2.88 \pm 0.08 \mu\text{m/h}$ and for the 30-hour data it is $2.86 \pm 0.11 \mu\text{m/h}$, where the errors refer to individual etch rate measurements.

The analysis of the 67 events with $Z \geq 40$ involved use of data in the form of etch rate V_i vs depth X_i in the stack and the Henke-Benton range-energy tables. For particles that stopped in the stack, the range R_i is of course directly known at each point. The statistic S used in the analysis of these particles is given by

$$S(Z) = \sum_{i=1}^N [V_i/V(\beta(R_i, Z, A), Z) - 1]^2, \quad (8)$$

where $V(\beta, Z)$ is defined by Eq. (7), $\beta(R, Z, A)$ is obtained by numerically inverting the range-energy relations that give $R(\beta, Z, A)$, and the mass num-

ber A is taken to be given by the empirical relation for the beta-stability line, $A = 2Z + 0.015 Z^{1.8}$.

For events that penetrated the stack completely the residual energy E' at exit becomes an additional free parameter, and we use the statistic

$$S(E', Z) = \sum_{i=1}^N [V_i/V(\beta(X_i + R', Z, A), Z) - 1]^2, \quad (9)$$

where $R' = R(E', Z, A)$.

The best estimate of Z is obtained by locating the minimum S_{\min} . We obtain 68% confidence interval limits by evaluating

$$S_{\pm 1\sigma} = S_{\min} [1 + p(n-p)^{-1} F(p, n-p, 0.317)], \quad (10)$$

where p is the number of free parameters and n is the number of data points.²⁷ The distribution $F(p, n-p)$, well known for its application in the F test, is used because there is no independent method of assigning the error to each measurement of etch rate. Sources of errors will be discussed in Sec. IV D.

The etch-rate data for the 67 events with $Z \geq 40$, several of which are shown in Fig. 8, were used

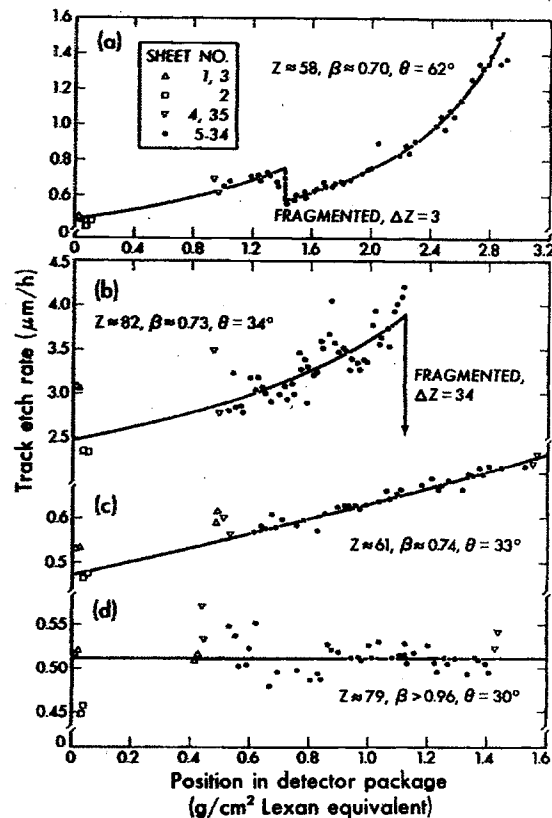


FIG. 8. Etch-rate response data for several ultraheavy nuclei, showing examples of fragmentations and small, systematic variations in response of sheets 1, 2, 3, 4, and 35.

to search for systematic variations in sensitivity of different Lexan sheets. For the "interior" sheets 5 through 34 no systematic variations were found. An occasional high or low etch rate in one sheet was uncorrelated with high or low etch rates in other sheets. The etch rates V_i for the top etch pit in sheet 4 and for the bottom etch pit in sheet 35 were systematically higher than the calculated rates $V(\beta(X_i + R', Z, A), Z)$ based on the data in all the sheets. Examples of these deviations can be seen in Fig. 8. The etch rates for both the top and bottom etch pits in sheet 2 were systematically slightly lower than the calculated rates. For sheets 1 and 3 there was no obvious trend, but the scatter of points was larger than for the data in sheets 5 through 34. This is not surprising, because the sheets are quite thin (75 μm), so that fractional errors in etch rate are large. Further, these 75- μm sheets were manufactured in a different batch from the 250- μm sheets and might be expected to have a different response.

We believe that the conservative approach, in examining the evidence that we have found a unique particle, is to disregard the data from these five sheets. Actually, the conclusions we will draw are not significantly affected by whether we include those data or not, because their error bars will be quite large.

For the interested reader, we summarize the results of the calibration of sheets 1 to 4 and 35 here. Least-squares lines through correlation plots of measured versus calculated etch rates for the 67 events led to the following correction factors to apply to etch rates in order to make Eq. (7) valid:

$$\text{sheet 1: } V_{\text{corr}} = (0.92 \pm 0.15) V_{\text{meas}}, \quad (11)$$

$$\text{sheet 2: } V_{\text{corr}} = (1.06 \pm 0.07) V_{\text{meas}}, \quad (12)$$

$$\text{sheet 3: } V_{\text{corr}} = (0.96 \pm 0.15) V_{\text{meas}}, \quad (13)$$

$$\text{top of sheet 4: } V_{\text{corr}} = (0.90 \pm 0.12) V_{\text{meas}}, \quad (14)$$

$$\text{bottom of sheet 4: } V_{\text{corr}} = (0.96 \pm 0.05) V_{\text{meas}}, \quad (15)$$

$$\text{top of sheet 35: } V_{\text{corr}} = (0.99 \pm 0.03) V_{\text{meas}}, \quad (16)$$

$$\text{bottom of sheet 35: } V_{\text{corr}} = (0.95 \pm 0.09) V_{\text{meas}}. \quad (17)$$

An adequate theory of errors in the track-etch process does not exist (see Sec. IVD). The error bars in Fig. 4 were arrived at in the following way. Restricting ourselves to the 28 sheets that needed no correction, we assumed that the deviations of the 56 data points from the true curve were normally distributed. As a working hypothesis we assumed the true curve to be the least-squares straight line through these 56 points,

$$V (\mu\text{m/h}) = (2.81 \pm 0.0479) \\ + (0.0674 \pm 0.0510) Y, \quad (18)$$

with Y = position in g/cm^2 Lexan equivalent, measured from the top of sheet 1. Requiring that the reduced chi-square $\chi_r^2 = 1$ gave a standard deviation for a single point, $\sigma = 0.0972 \mu\text{m/h}$. We determined the σ 's for sheets 1, 2, 3, 4, and 35 by adding in quadrature this σ to the appropriate values derived from the errors in Eqs. (11) to (17).

C. Fragmentation within the Lexan stack

The published interpretations³⁻⁶ of the monopole candidate as a normal nucleus with $Z \leq 96$ required at least one fragmentation, and we now discuss that possibility. It has been assumed since the earliest studies of heavy nuclei in the cosmic rays and has recently been established in Bevalac experiments²⁸ that, in fragmentation of a fast-moving heavy nucleus with loss of only a few nucleons, the speed and direction of the residual nucleus remain almost unchanged. In the frame of the moving nucleus the parallel components of momentum have a most probable value $\sim 10^2 \text{ MeV}/c$ and both the perpendicular and parallel components have a Gaussian distribution with $\sigma \approx 10^2 \text{ MeV}/c$.

When a heavy nucleus fragments in a Lexan stack the residual nucleus often is heavy enough to leave a detectable track and the etch rate data show a discontinuity at the point where fragmentation occurred. To date, only the residual nucleus has been detected in Lexan, the light fragments having too low an ionization rate to be recorded.

Figure 8(a) contains an example of a fragmentation with $\Delta Z = 3$. In the case of a slowing particle with a detectable etch rate gradient, the gradient *decreases* after the interaction because the residual nucleus, being lighter, has a greater range than the initial nucleus even though its velocity is the same. Thus the portion of the etch rate curve after fragmentation does not exactly map onto an extension of the etch rate curve before fragmentation by a simple upward translation but has a smaller slope as well as magnitude. In practice the decrease in slope may be too small to detect.

Fluctuations in etch rate are sufficiently small that one can usually be certain of detecting fragmentations with $\Delta Z \geq 3$ unless they occur in one of the top two or bottom two sheets of a stack. Fragmentations with $\Delta Z = 1$ or 2 are difficult to distinguish from a series of correlated deviations in etch rate, some of which are not obviously indicative of fragmentation. Figure 8(b) shows examples of such correlated deviations.

Of the 67 particles with $Z \geq 40$, four definite fragmentations with $Z \geq 3$ were observed to occur

between sheets 4 and 28. The total pathlength traversed was 25.3 cm and the changes in charge were 3 [shown in Fig. 8(a)], >8 , >16 , and 34 [shown in Fig. 8(b)]. From the Skylab experiment,⁹ in a total pathlength of 68 cm eight interactions were observed having $\Delta Z=3, 3, 4, 5, 10, 17, >16$, and 17. Because of the scanning criterion requiring a coincidence between etch pits in widely separated sheets, the number observed on Skylab is probably an underestimate. Nevertheless, in both cases the frequency of detectable fragmentations, ~ 0.12 to ~ 0.16 per cm, is quite consistent with the probability of an interaction with $\Delta Z \geq 3$ of nuclei with $40 \leq Z \leq 92$ in Lexan, estimated from the geometric cross section.

At a depth of ~ 1.1 g/cm² in the stack, the data in Fig. 4 show a glitch that has been commented on by critics and cited by one⁴ as evidence of an "obvious fragmentation." The magnitude of the discontinuity corresponds to $\Delta Z \leq 2$, which we have said is insufficient proof of a nuclear fragmentation. The slope after the glitch is not smaller, as it should be if the glitch signified a fragmentation, but larger than before the glitch. It may be an example, like those in Figs. 8(b) and 8(d), of correlated fluctuations of unknown origin, possibly even statistical. If the four low data points immediately following the glitch are removed, one will not notice a glitch; these four points come from cones in only two sheets. The last four points (in sheets 34 and 35) actually lie well below the curve for a fragmenting nucleus, as will be seen in Fig. 9. Our view, and that expressed by other nuclear-track experts, is that "the scatter in the data is such that an interaction is by no means demonstrated, but it is certainly not ruled out" (quoted from Ref. 6).

D. Large fluctuations in effective charge?

It is necessary to consider whether the monopole candidate can be explained in terms of a chance occurrence whereby a slow, heavy ion attaches a sufficient number of electrons at the appropriate spatial locations to mimic a more rapidly moving, heavier ion. In principle, an advantage of this atomic mechanism over the nuclear fragmentation mechanism would follow from the relatively large cross sections typical of atomic processes, which might remove the need to invoke very small probabilities of occurrence. For $Z/\beta \approx 114$ and $\beta < 0.6$ the ion slows so rapidly that the required large number of attached electrons is easily ruled out, and we consider only the intermediate velocity regime $\beta \approx 0.6$ to 0.7 . Fowler *et al.*,¹⁸ and more recently Wilson,²⁰ have discussed quantitatively the competition between the electron stripping process and the two processes of nonradiative and

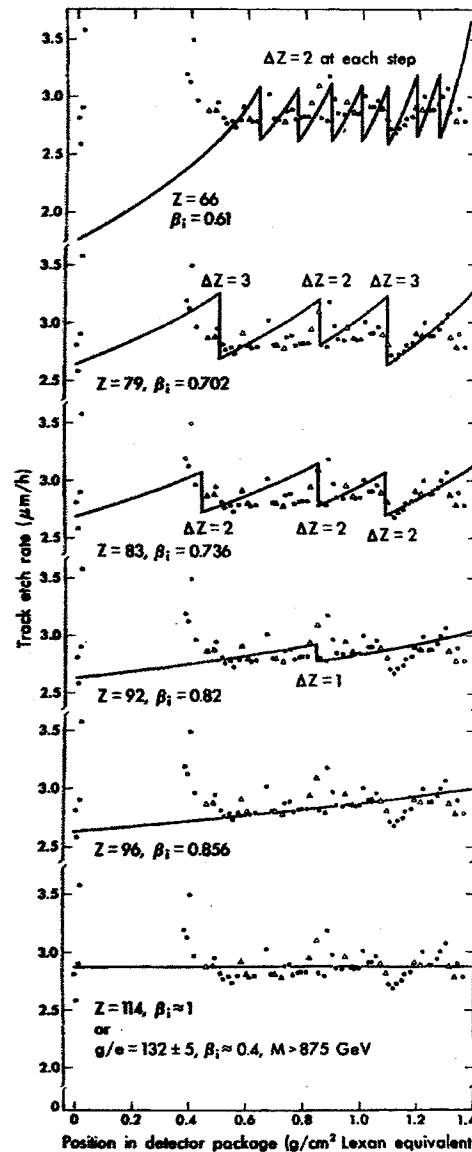


FIG. 9. Response curves for several combinations of initial Z and β and fragmentations that approximately pass through the data. If the initial β is small, the number of successive fragmentations must be large.

radiative attachment, as a function of the velocity and charge of the moving nucleus and the charge of the medium traversed. The results of recent measurements of electron-attachment cross sections,²⁰ made at the Bevalac, support their conclusion that the radiative process dominates over the nonradiative process at the velocities relevant to the present case. Both theory and the empirical expression in Eq. (1) agree that a heavy nucleus with $Z/\beta \approx 114$ and $\beta \approx 0.6$ to 0.7 will retain one or

possibly both of its K electrons. However, in order to maintain a roughly constant ionization rate through the stack, the number of electrons attached would have to grow to ~ 10 to 16 , which seems farfetched for two reasons. Though a quantitative theory of attachment and stripping cross sections of L , M , ... electrons has not been developed, the qualitative argument of Bohr,³¹ that an ion retains only those electrons with speed comparable to or greater than the ion's speed, would indicate that electrons less tightly bound than K electrons to a nucleus with $Z/\beta \approx 114$ and $\beta \geq 0.6$ will not be attached. Further, if numerous electrons in higher than K shells could be readily attached, it would be virtually impossible to identify high-energy heavy nuclei because of the extremely large fluctuations of effective charge. This is in direct contradiction with the large number of measurements of etch rate vs depth in Lexan stacks and with the quite reasonable charge distributions obtained for the ultraheavy cosmic rays.^{7,9,10,21} Finally, even if a partially stripped nucleus with β as low as 0.6 could maintain $Z^*/\beta \approx 114$ and account for the Lexan data, its distant energy deposition would be too high to fit the data in the three emulsions. For example, its track structure would look similar to that in Fig. 14(b) of the nucleus with $Z = 75$, $\beta = 0.67$, rather than like that of the monopole candidate in Fig. 14(a).

E. Sources of errors in etch rates

At present, our understanding of Lexan detectors is inadequate for us to discuss errors from first principles. Our discussion must be somewhat phenomenological. For the monopole candidate the etch rates in sheets 5 to 34 appear to be normally distributed about the line in Eq. (18) with a fractional standard deviation $\sigma/\bar{V} = 0.0972/2.86 = 0.034$. For the other particles from the Sioux City flights the fractional errors for a single point have a median value of 0.035 and range from 0.018 to 0.074 , taken with respect to curves calculated from Eq. (7). Half of them fall between 0.027 and 0.04 . The magnitude of the fractional error does not appear to correlate with either Z or β . For the Skylab experiment⁹ the median value was 0.025 . The scatter in the measurements for the monopole candidate appears to be typical of ultraheavy cosmic-ray measurements.

Sources of error include those due to measurement errors and those due to physical and chemical effects.⁹ Measurement errors account for a length error of $\sim 0.8 \mu\text{m}$, which amounts to a fractional error of only 0.010 for the monopole candidate. Physical effects include statistical fluctuations in the energy deposited by the numer-

ous electrons with energy less than $\sim 1 \text{ keV}$, electron capture and loss processes that change Z^* abruptly, fragmentations that change Z abruptly, and mechanical deformation of the Lexan stack, which might affect detector response. Statistical fluctuations in the production rate of low-energy electrons contribute a negligible error. For a nucleus in a certain range of energies that depends on Z , capture and loss of electrons result in a variability of Z^* by one unit, which could in principle be detected if other contributions were sufficiently small. For capture of an electron by a nucleus with $Z = 80$, the etch rate would decrease by $\sim 6\%$. Nuclear fragmentation happens too rarely to explain more than an occasional fluctuation. No obvious mechanical deformation of module 104, containing the monopole-candidate track, was observed.

Chemical effects include inherent microscopic variability in structure and composition of the Lexan sheets, variability associated with the etching process, and variability of the chemical environment during and after the balloon flights. The first of these is probably the major source of the uncorrelated errors. This conclusion is supported by recent work³² in which a more homogeneous plastic than Lexan was found with a response showing a much smaller fractional error than that for Lexan. The second chemical effect is probably negligible for all sheets etched in the same well-stirred solution. The third probably at least partly explains the systematic errors observed in sheets 1, 2, 3, 4, and 35. We give three examples. (1) Oxygen and other gases dissolved in Lexan are known to play a role in fixation of the latent track.² External sheets may be exposed to greater changes in ambient gas composition during the balloon flight than do sheets inside the bolted stack. (2) Over a period of months, mold slowly grows on Lexan and may affect track etch rates of sheets exposed in the storage area. (3) Lexan in contact with adhesive tape or even dissimilar plastic seems to give a larger variability in etch rates than Lexan in contact with other sheets of Lexan.

The Lexan modules were assembled by stacking pieces successively cut from a single roll. The apparently correlated errors in several successive sheets might be explained by systematic variability along the original roll.

V. TESTS OF HYPOTHETICAL FITS TO LEXAN DATA

Not every physicist accepts statistical analyses of experimental data, perhaps partly because of the frequency with which 3σ or 4σ effects are claimed and later disappear when the experiment is repeated. The material in this section is in-

cluded for those who find it useful to have an objective, quantitative comparison of the quality of fits of various hypothetical curves to the Lexan data alone. First we evaluate the goodness of fit of nuclei with various initial charges and velocities that fragment zero or more times with integral loss of charge at arbitrary positions in the stack. Then, following Fleischer and Walker,⁶ we estimate the total probability of a particular scenario occurring in either the Minneapolis, Skylab, or Sioux City flights. The overall figure of merit for a hypothesis will be taken as the product of the confidence level for the fit to the data and the total probability of occurrence of that scenario.

The χ^2 test is very commonly used as a measure of goodness of fit but requires an independent knowledge of the error for each point. The Particle Data Group finds³³ that particle-physics experimentalists often underestimate σ . As a rule, when the quantity $\chi^2 = \sum_i (x_i - \bar{x})^2 / \sigma_i^2$ is significantly greater than the number of degrees of freedom in a particular experiment, the Particle Data Group multiplies the σ 's by a scale factor, typically of order 1.34, so that the reduced χ^2 is of order 1. In effect, we used similar reasoning when we chose $\sigma = 0.0972 \mu\text{m/h}$ in order that $\chi^2/\nu = 1$ for the distribution of etch rates about a straight line for the monopole candidate.

The F test is a better, more conservative way of comparing the variances of two hypothetical curves through a set of data than is the χ^2 test. The statistic F is defined as the ratio of reduced χ^2 's for the two curves. If it is known that all points have the same σ , then the F test does not require σ to be known because its square appears in both numerator and denominator. In our case we use the 56 data points from sheets 5 through 34, which had the same sensitivity, and ignore the data from sheets 1, 2, 3, 4, and 35, which had larger errors, arising from both normalization and inherent errors. Thus F is given simply by the ratio of variances and is independent of the size of the er-

ror bars. (Note that the χ^2 test, which requires a knowledge of σ , is a limiting case of the F test when one hypothesis has an infinite number of degrees of freedom.) If one wished to force an acceptably high confidence level using the χ^2 test, one could, if they were not independently known, arbitrarily inflate the σ 's until some arbitrary, quite unlikely hypothesis gave a reduced $\chi^2 \approx 1$.

We assume, as is customary in statistics,³⁴ that of two hypotheses compared by means of the F test, the one with the higher confidence level is the more likely. For convenience, we take as the baseline hypothesis the least-squares straight line given by Eq. (18). Column 4 of Table II lists F -test confidence levels for several combinations of β , Z , and types of fragmentations. Figure 9 shows curves for several hypothetical cases that approximately pass through the data. The curves are the results of calculations in which, for a given number of fragmentations, the values of initial β and Z and the positions and ΔZ values of fragmentations were calculated to minimize the square error. It is interesting that a lower square error is achieved for a single fragmentation that occurs near the middle of the stack rather than at the glitch at 1.1 g/cm^2 . The conclusions in Table II are insensitive to the precise positions of the fragmentations.

Note that the number of fragmentations required to fit the data at a specified confidence level increases rapidly as the assumed initial velocity decreases. For a fixed number of fragmentations the confidence level decreases rapidly as the initial velocity decreases.

If, instead of the F test, one uses the χ^2 test with the σ 's chosen so that $\chi^2_\nu \approx 1$ for the least-squares straight line, then the confidence levels for the various nuclei are considerably lower, typically by a factor ~ 10 for $\beta \leq 0.8$.

Column 5 of Table II gives the integrated probability for finding, in some flight, an event of the type described. It is equal to the product of the

TABLE II. Likelihood of nuclear fit to Lexan data for several initial velocities.

Initial β	Best initial Z	No. of fragments	Confidence level from F test	Total probability in any flight	Likelihood (col. 4 \times col. 5)
> 0.99	114 ^a	0	0.6	?	?
0.952	108 ^a	0	1	?	?
0.856	96	1	1	0.3	0.3
0.820	92	1	0.1	0.3	0.3
0.744	82	2	0.005	0.005	2×10^{-5}
0.704	76	2	10^{-5}	0.005	5×10^{-8}
0.600	67	8	0.1	10^{-17}	10^{-18}

^a Note that no elements with $Z > 96$ have been seen before in the cosmic rays and no elements with $Z > 106$ have been made in accelerators.

total number of similar tracks of nuclei in a suitable range of Z and β seen in all experiments times the probability of occurrence of that number of fragmentations by a single nucleus. We took for the pool of nuclei those seen in the Minneapolis, Skylab, and Sioux City flights with initial etch rates greater than those corresponding to $Z^*/\beta = 100$ and gradients less than those corresponding to $\beta = 0.65$. In the Minneapolis experiment⁷ four such particles were seen. Their initial values of Z and β were 90, 0.7; 74, 0.72; 80, 0.76; and 82, 0.74. None of these nuclei fragmented, so their etch rate curves rose steeply with depth in the stack. In the Skylab experiment one nucleus was detected with $Z = 82$, $\beta = 0.68$, and Z/β increasing from 121 to 153 through the stack. In the Sioux City experiment, in addition to the monopole candidate there were four events with initial $Z^*/\beta > 100$ and $\beta \geq 0.65$. The total number of observed particles that might fragment such as to mimic a particle with a constant, very high ionization rate implying an apparent $Z \geq 110$ is taken conservatively to be ten.

To calculate the probability of a single interaction of appropriate type in the $\sim 0.9 \text{ g/cm}^2$ of Lexan between sheets 5 and 34, we assumed the same fragmentation mean free path as did Fleischer and Walker⁶ as modified in their footnote 14. We assumed that $\Delta Z = 1$ or 2 at any interaction would give an acceptable fit for any of the fragmentations in Table II, so that $\lambda \approx 29 \text{ g/cm}^2$. Following Fleischer and Walker, as a rough estimate of the probability of an optimum spacing of the interactions within the stack, we included the additional factor $n!/n^n$, where n is the number of interactions to be put into n separate compartments. Column 6 of Table II gives the figure of merit for each hypothesis, defined as the product of column 4 and column 5.

One could apply additional tests to the data; for example, the "run test" examines the hypothesis that the data are randomly distributed above and below a particular curve. We believe it is sufficient, however, to end this section by stating the following two noncontroversial conclusions: (1) In the absence of information from other detectors, the monopole candidate would be perfectly consistent with a once-fragmenting nucleus with $Z = 90$, 92, 94, or 96. (2) If the particle was a nucleus, the confidence level that its velocity was as low as $0.6c$ is vanishingly small.

VI. ANALYSIS OF THE NUCLEAR EMULSIONS

A. General

For the benefit of the reader who is not interested in the details, we state here the main result of

the analysis of the emulsion data. Outside of the cylindrical region of very heavily developed grains a few microns in radius, the energy deposited by energetic knockon electrons was much lower for the monopole candidate than expected for a known, long-lived nucleus with $Z \leq 96$, $Z/\beta \approx 114$, and $0.84 \geq \beta \geq 0.6$, and appears to be similar to that expected for a nucleus with $Z/\beta \approx 85$ and $\beta \geq 0.6$.

The response of nuclear emulsion to a charged particle is, in a sense, complementary to the response of Lexan. The track etch rate in Lexan depends on energy deposited in a cylinder of radius $\leq 10^{-6} \text{ cm}$ predominantly by very low-energy electrons and is completely insensitive to energy deposited at large radial distances. The density of developed silver grains in electron-sensitive emulsion such as we used is a measure of the density of energy deposited primarily by knockon electrons. Within a radial distance of ~ 2 to $\sim 6 \mu\text{m}$ the grain density for a very heavily ionizing particle is too high to give quantitative information. At greater distances the radial distribution of silver grains gives a useful measure of the knockon-electron energy spectrum. Lexan responds to very low-energy electrons produced in distant encounters, giving an accurate measure of $|Z|/\beta$, whereas emulsion gives in convoluted form the energy dependence of the cross section for production of high-energy electrons in close encounters. The Rutherford scattering cross section, though an adequate approximation for distant encounters of a highly charged particle and a free electron, is incorrect for close encounters. The relevant cross section will depend on the particle: For a point nucleus or antinucleus the Mott cross section is relevant³⁵; for a monopole the cross section recently calculated by Kazama, Yang, and Goldhaber is relevant³⁶; and for an extended particle with arbitrary charge distribution a still different cross section dependent on the form factor would apply.

A quantitatively correct relationship between the silver grain density as a function of position in the emulsion and the Z , β , and zenith angle of the particle would depend on a number of factors, the detailed dependence being still controversial. Three models relating the spatial variation of silver grain density to Z and β exist—the unpublished model of Osborne, based on the calculations of Katz and Kobetich,³⁷⁻³⁹ the approximate analytic model of Fowler,¹⁶ and the unpublished, detailed, physical model of Hagstrom,¹⁴ which uses a Monte Carlo program. Though these models differ in some of the detailed conclusions regarding the monopole candidate, they agree in the following generalizations noted by Hagstrom¹⁴:

- (1) Saturated darkening due to developed silver

grains in the so-called core of the emulsion track results from knockon electrons with energies $1 \leq E \leq 50$ keV, whereas unsaturated but easily visible darkening in a halo of extent ~ 10 to ~ 30 μm from the core results from knockon electrons of energies $25 \leq E \leq 1000$ keV.

(2) Given the constraint imposed by the Lexan, $|Z|/\beta = 114$, the energy deposition in the core is virtually independent of Z .

(3) Among the positive nuclei with $Z \leq 96$, $\beta \geq 0.6$, and $Z/\beta = 114$, energy deposition in the 10- to 30- μm halo depends only very weakly on Z .

In the next subsections we present several types of measurements on the three layers of nuclear emulsions showing that the energy deposition in the halo was significantly depleted from that expected for the known, long-lived nuclei with $Z \leq 96$, $\beta \geq 0.6$, and $Z/\beta = 114$, thus establishing at a high confidence level that the particle was unique.

B. Visual measurements of R_1 and R_2

The traditional method for inferring the radial distribution of energy deposited around a track has been to use a photodensitometer¹⁸ to measure the attenuation of a pencil of light transmitted through a column of the emulsion defined by a small slit. A disadvantage of this method is that it integrates along a column containing silver grains at varying radial distances from the trajectory. Some years ago one of us (W.Z.O.) began developing a system called AMID (automated microscopic-image dissector), which could recognize individual grains, automatically scan the volume of emulsion around a track, record the locations of silver grains, subtract background, and compute the radial distribution of silver grains. Only now has the system begun to be employed on a substantial number of events. Before the system became operative, W.Z.O. found that it was possible to make fairly reproducible visual measurements of the radial distances at which two specific levels of darkening occurred, using a calibrated eyepiece reticle in a microscope. These two radial parameters are called R_1 , the radius of the core of complete darkening, and R_2 , the radial distance at which the halo of partial darkening drops to the background level. The values of R_1 and R_2 were measured for the ultraheavy cosmic-ray tracks in the Minneapolis flight but have not previously been published; the values of R_1 and R_2 have been reported for the monopole candidate¹ but not for the other ultraheavy events in the Sioux City flights.

R_1 , the radius of the core of saturated darkening near the center of the track, is obtained by using a $53\times$ oil objective with high numerical aperture

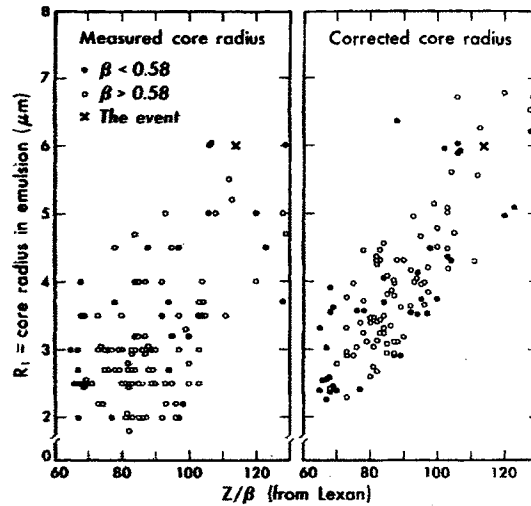


FIG. 10. Observed correlation of core radius R_1 with Z/β for slow ($\beta < 0.58$) and fast ($\beta > 0.58$) particles in the Minneapolis and Sioux City flights. The point for the monopole candidate is labeled X. A geometric correction that takes into account distortion due to shrinkage of the emulsion gives the improved correlation shown on the right.

($NA = 0.95$), focusing along the center of the track, and estimating the average radius of the completely dark central region. For very steep tracks R_1 is measured by focusing at the interface between the bottom of the emulsion and the plastic backing. Measurements of R_1 for events from the Minneapolis and Sioux City flights are shown in the left-hand side of Fig. 10 as a function of Z/β . The latter quantity was calculated at the emulsion from the set of measurements made in the Lexan stack after the core radii were measured. Rather surprisingly, we found no systematic difference in the dependence of R_1 on Z/β for the two flights and so the same symbols are used for both sets of data.

For both R_1 and R_2 (see Fig. 11) we show separately the data for events at low velocity ($\beta < 0.58$) and at high velocity. In accord with track models, we see that R_1 increases approximately linearly with Z/β and does not depend on β alone. The dispersion of points is much greater than that due to measurement error ($\Delta R_1 \approx \pm 0.5$ μm). It was pointed out in the status report on the monopole candidate¹³ that R_1 depends rather strongly on zenith angle θ : Steep tracks have a larger core width than do shallow tracks with the same Z/β . This is a well-known consequence of distortion during processing of the emulsion. During fixing, the undeveloped silver halide grains are removed, the emulsion shrinks in thickness, and the dense mass of silver grains in the core, being much less

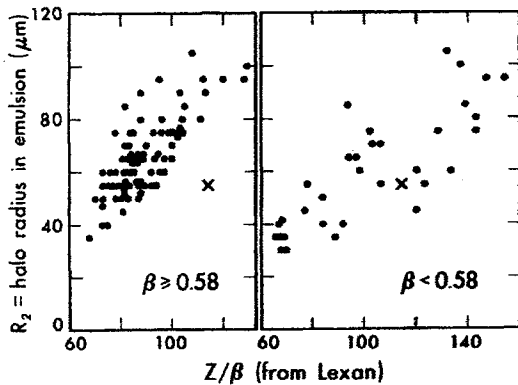


FIG. 11. Observed correlation of halo radius R_2 with Z/β . The halo radius for the monopole candidate, labeled X , is much less than expected if it were a nucleus with $\beta \geq 0.58$. The data show that slow nuclei ($\beta < 0.58$) tend to have smaller halo radii than fast nuclei with the same Z/β .

compressible than the gelatine, is displaced outward in order to conserve volume.^{3,40} The lateral displacement is a maximum for a vertical track and is almost zero for a horizontal track. If one fails to control processing properly and overdevelops the emulsion, the silver grains may grow so large that the core becomes a solid wire that punches through the surfaces of the shrinking emulsion rather than deforms with the emulsion.⁴⁰ No cases of punchthrough were observed for tracks in the emulsions used in the Sioux City flights.

For properly developed emulsion it is straightforward to apply a geometric correction to the measured core radii in order to infer the core radii before shrinkage. The points on the right-hand side of Fig. 10 have been corrected, assuming a density of silver grains that falls off as $(Z^*/\beta r)^2$, a volume per grain that is a free parameter, and a shrinkage factor, S , defined as the ratio of initial to final emulsion thickness, that is directly measured. For the data in Fig. 10, we chose to normalize the correction so that the core radius for the monopole candidate (with $\theta = 10^\circ$) would be unchanged. The essence of our calculation of corrected core radii can be reproduced by a simple one-parameter model involving only the shrinkage factor, the zenith angle θ , and the assumption of a deformable, incompressible fluid whose initial radius R_{1i} is related to its final radius R_{1f} as follows:

$$R_{1i} = R_{1f} (\sin^2 \theta + S^{-2} \cos^2 \theta)^{1/4}. \quad (19)$$

Of course, θ is the true zenith angle, which we determined by measurements in the Lexan stack.

After correction, the dispersion is much reduced and is consistent with measurement error alone.

Though the corrected core radius is rather insensitive to the identity of the particle, one can say from the position of the data point for the monopole candidate that both the Lexan and the core radii agree that the particle behaved in its close energy deposition like a particle with $|Z|/\beta \approx 114$. Hagstrom has pointed out that the tightness of the correlation provides strong evidence that the cylindrical region of emulsion of radius $\sim 6 \mu\text{m}$ traversed by the monopole candidate had closely the same sensitivity as the other emulsions. If, for example, we were to propose that the deficiency of silver grains at large radial distances (to be presented below) was caused by passage of a normal nucleus with $Z/\beta = 114$ through a very insensitive region of emulsion, then the corrected core radius would also have to reflect a deficiency of silver grains, i.e., it would lie well below the population of points for emulsion of normal sensitivity. Measurements of Fe tracks, to be presented later, show that over dimensions of many centimeters the sensitivity of the emulsion in module 104, containing the monopole candidate, was indistinguishable from the sensitivity of the emulsion in the other modules. Figure 10 shows that the sensitivity of the emulsion was normal within a few microns of the region in which the energy deposition was observed to be abnormally low.

Next we discuss R_2 , which is a visual measure of the distant energy deposition. At low magnification, $\sim 80\times$, the eye perceives that the darkening resulting from energetic knockon electrons decreases with radial distance and becomes indistinguishable from background at some distance we call R_2 . It is impossible to describe quantitatively how the eye evaluates R_2 , and the decision as to where the signal fades into background is likely to be somewhat subjective. This is a serious drawback to the use of data for R_2 as evidence for a unique particle. (The photographic results, to be presented in Sec. VID, and the AMID measurements in the thin emulsions, to be presented in Sec. VIE, are particularly important because they provide objective measurements of the distant energy deposition.) The measurements shown in Fig. 11 were made at Houston by W.Z.O. before the events were located in Lexan and assigned values of Z and β . Events for both Minneapolis and Sioux City flights are included, and data for low and high velocities are plotted separately. It is perhaps surprising that reasonably consistent results are obtained for two exposures of such different duration as Sioux City and Minneapolis.

In contrast to the situation in Fig. 10, where the energy deposition at distances of only a few microns depends only on Z/β , not on β , in Fig. 11

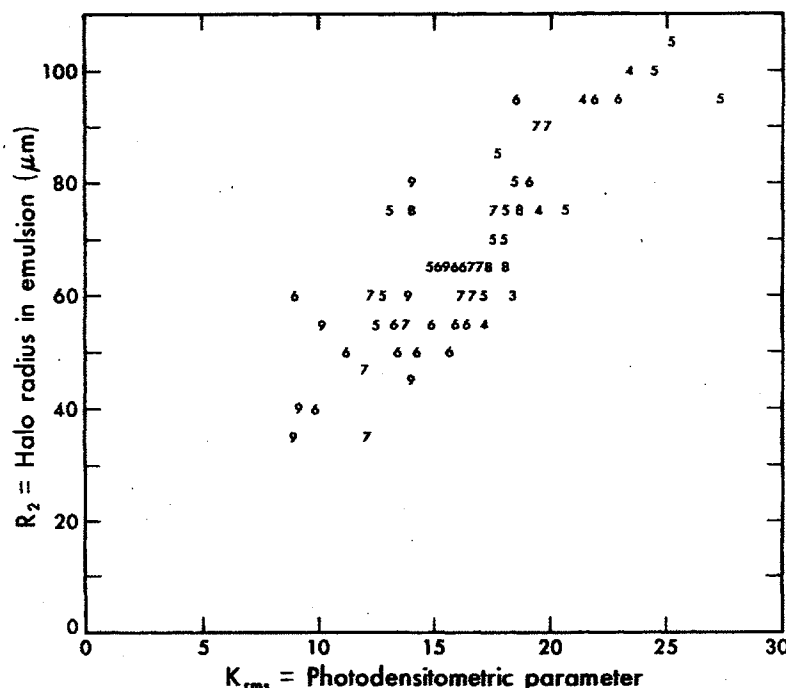


FIG. 12. Comparison of halo radius, measured visually in the G-5 emulsion, with the quantity K_{rms} , which is a measure of the optical density distribution determined with a photodensitometer. Each point is labeled by the value of β truncated in tenths.

we see that the energy deposition at large distances (tens of microns) can depend both on Z/β and β . For the ordinary nuclei, denoted by black points, R_2 correlates well with Z/β for values of $\beta \approx 0.58$, in accord with track-structure models. The generally lower values of R_2 at a given Z/β for ordinary nuclei with low velocity are expected because of kinematic effects such as the cutoff in the electron energy spectrum at $w_{max} = 2m_e c^2 \beta^2 \gamma^2$. The models differ so much in the quantitative details of how the energy deposition depends on β and radial distance for low-velocity particles that we make no attempt here, as we had earlier, to infer the velocity of the monopole candidate from the measurements.

The reader cannot fail to note that the point for the monopole candidate, labeled X, does not seem to be a member of the population of events with $\beta \geq 0.58$. Instead of having a halo radius of nearly 100 μm , as did the several fast particles with $Z/\beta \approx 110$ to 120, it had a halo radius of only 55 μm , like fast particles with $Z/\beta \approx 80$. In the right-hand side of Fig. 11 one sees that the point for the monopole candidate is bracketed by data for particles known to have $\beta < 0.58$. Endowing the particle with a low velocity is one way to account for the anomalously small value of R_2 , provided its mass is made large enough so that its constant

ionization rate in the Lexan stack can be understood. We will see later that the required mass would be so large ($\geq 10^3$ amu) that nuclei are excluded.

C. Photodensitometry; relative sensitivity of emulsions

Using a Perkin-Elmer PDS Microdensitometer Model 1010A in the Astronomy Department at Berkeley, we have made two sets of measurements of tracks in the Ilford G-5 emulsion from the Sioux City flight. With Fowler and Henshaw of the University of Bristol, we have found⁴¹ that measurements of optical density as a function of lateral distance from tracks in emulsion made with the PDS and with the Bristol densitometer on the same events give extremely good agreement. A separate paper⁴¹ describes the PDS and the techniques of track densitometry.

In the first set of measurements we wanted to see if the visual quantity R_2 , which might be subject to error due to peculiarities in the physiology of vision, was closely correlated with the darkening of the emulsion around a track as measured by its optical density relative to background.

Figure 12 compares measurements of R_2 with photodensitometric measurements for the same set of tracks from the Sioux City flights. (No PDS

measurements were made on the Minneapolis tracks.) The abscissa, K_{rms} , is a measure of the optical density,⁴¹ obtained by minimizing the sum

$$\chi^2(K) = \sum_x [D(x) - \bar{P}(K, x, t, \theta)]^2, \quad (20)$$

where $D(x)$ is the optical density measured at a

lateral distance x from the projection of the track axis and \bar{P} is a theoretical expression¹⁶ for the average projected density of silver grains in a column at distance x sampled by a long, narrow slit of length $\Delta y = fL \sin \theta$ and width $\Delta x \ll \Delta y$ (rewritten in our nomenclature):

$$P(K, x, t, \theta) = \frac{2K^2 \csc \theta}{fx} \left\{ \frac{1+f}{2} \arctan \left[\frac{(1+f)t \sin \theta}{2x} \right] - \frac{1-f}{2} \arctan \left[\frac{(1-f)t \sin \theta}{2x} \right] \right. \\ \left. - \frac{x}{2t \sin \theta} \ln \left[\frac{1 + (1+f)^2 t^2 \sin^2 \theta / 4x^2}{1 + (1-f)^2 t^2 \sin^2 \theta / 4x^2} \right] \right\}. \quad (21)$$

Here t is the emulsion thickness, $L \sin \theta$ is the projected length of the track, and the slit length was set for each track to be 20, 60, or 100 μm such that $f \leq 0.8$ in order to exclude the portions of the track nearest the two surfaces, where transition effects are large. The slit width was $\Delta x = 5 \mu\text{m}$ and readings of $D(x)$ were taken automatically every 2 μm . The sum in Eq. (20) is over data for $|x| = 4$ to 100 μm and for which the density is more than 2σ above background. The values of $D(x)$ were taken relative to a background level given by the average density in two strips at $x = -150$ to $-130 \mu\text{m}$ and $x = 130$ to $150 \mu\text{m}$.

K includes all the physics of grain sensitization, the chemistry of development, and the optics of observation. When χ^2 is minimized, the value of K_{rms} is found,⁴¹ in accord with track models, to increase roughly linearly with Z/β for high-velocity particles and to show a velocity dependence for particles with $\beta \leq 0.6$. Data showing the dependence of K_{rms} on Z , β , and θ are presented in Ref. 41.

The good correlation between R_2 and K_{rms} in Fig. 12 for velocities ranging from 0.36 to 0.98 c suggests that physiological effects such as the difficulty of seeing gradual spatial variations in brightness do not seriously impair the usefulness of R_2 as an indicator of the magnitude of energy deposition at several tens of microns.

The results in Fig. 12 strengthen our confidence in the significance of the discrepancy for the monopole candidate, shown by the X in Fig. 11. It is unfortunate that we cannot report reliable densitometric measurements of the monopole-candidate track itself. During intensive microscopic study and photography of the event by Hagstrom, the emulsion was exposed to illumination so intense that the track was distorted into a C shape. Straightforward corrections for the distortion (discussed in Ref. 40), utilizing neighboring tracks of relativistic α particles, allow one to

reconstruct the positions of the grains to within a few microns. This makes feasible the determination of the radial distribution of grain density with AMID. Fortunately a set of photomicrographs at about 40 positions along the track, including the micrograph in Fig. 14(a), were completed before the damage occurred.

The second set of measurements was designed to search for possible systematic variations in sensitivity within the Ilford emulsion in module 104 and from module to module. If, for example, it turned out that the emulsion in module 104 was much less sensitive than the other emulsions, due perhaps to an accident in manufacture or in development, then the low density of grains at large radial distances for the monopole candidate would have a trivial explanation.

Variations in response of emulsion can be caused by variations in its initial chemical or physical state; variations in its history prior, during, or after exposure, and variations in the degree and type of development. Previous studies of emulsion sensitivity have included, *inter alia*, counts of blob density along tracks of minimum-ionizing protons,⁴⁰ photodensitometric measurements of the magnitude of fluctuations in the optical density of the emulsion as a function of position,¹⁶ and photodensitometric measurements of tracks of Fe nuclei.¹⁶ The latter method, though laborious, is the best because it measures most directly the relevant quantity, the production of silver grains due to energetic knockon electrons.

In addition to module 104, which contained the monopole-candidate track, we chose seven modules containing tracks of ultraheavy cosmic rays with zenith angles or Z/β similar to those of the monopole candidate. One of the modules, No. 76, contained an event with $Z/\beta = 112$, $\theta = 14^\circ$ [photographed in Fig. 14(b)], nearly identical to the values for the monopole candidate. We first compared the average background optical densities of

the eight emulsions, correcting for differences in thickness. We determined the thickness of emulsion in the vicinity of an ultraheavy cosmic-ray track by measuring the projected length of that track and of several nearby Fe tracks, assuming only vertical shrinkage without shear, and determining the true zenith angles of these tracks from measurements in the Lexan stack adjacent to the emulsion. All of the emulsions had average optical densities per unit thickness that agreed within ~1%, indicating a high degree of uniformity of initial sensitivity and of degree of development.

Next, from measurements in the Lexan we selected 56 tracks of nuclei identified as having $Z=26$ and with similar zenith angles, 35° to 45° , and similar Z/β , 59 to 68, at the emulsion. Twenty-one of the tracks were distributed throughout module 104. The first set of data were obtained at $2\text{-}\mu\text{m}$ intervals for $|x| \geq 4\text{ }\mu\text{m}$ in the same way as the measurements were made for the heavier nuclei. For each track we calculated K_{rms} as described earlier. Assuming an approximate proportionality to (Z/β) ,

$$K_{\text{rms}} = C_1(Z/\beta), \quad (22)$$

we found for the entire sample $C_1 = 0.153 \pm 0.015$, and for the 21 tracks from module 104, $C_1 = 0.152 \pm 0.020$. These results show that the average sensitivity of the region of emulsion in module 104 is indistinguishable from the average sensitivity of the emulsion in the other seven modules. For the sample of Fe tracks Z , β , and Z/β are known quite accurately because each event was traced to the end of its range in the Lexan stack and several measurements of etch rate were made at known residual ranges. If one were to use these emulsions to determine Z/β for unknown particles with about the same ionization rate as in the sample, one could determine Z/β with a fractional error of ~10%. Although calibration particles with a higher Z/β are not yet available, we expect the fractional error for the ultraheavy cosmic-ray tracks to be considerably smaller because of the greater signal.

The density of silver grains around Fe tracks is considerably lower than that for the ultraheavy cosmic-ray tracks. To get a greater signal for the sample of Fe tracks we made a second set of measurements, with a slit of width $\Delta x = 5\text{ }\mu\text{m}$ and length $\Delta y = 100\text{ }\mu\text{m}$ centered on the track core. Figure 13 shows the data. At the track axis the gradient of light across the width of the slit is particularly large, and the central density does not respond linearly to silver grain density. Denoting the central density by D_c , we utilize the relation determined empirically by Fowler *et al.*,¹⁶

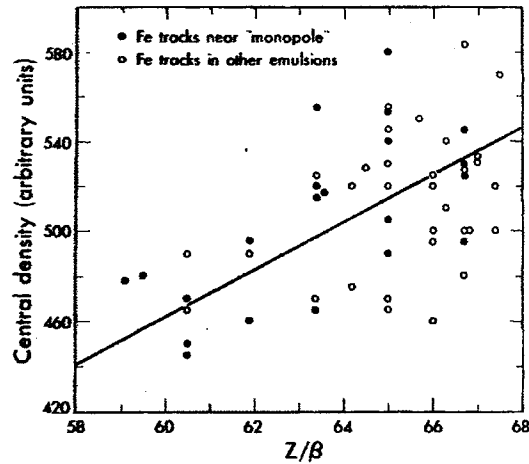


FIG. 13. Evidence that the sensitivity of the region of G-5 emulsion near the monopole candidate track was closely the same as the sensitivity of the emulsions traversed by other ultraheavy cosmic rays. The photo-densitometric readings with the slit centered on the track axis show the same distribution with Z/β for Fe tracks near the monopole-candidate track and in other emulsions.

$$D_c = C_2(Z/\beta)^{1.34}, \quad (23)$$

which accounts approximately for the nonlinear response. A least-squares fit of all of the data to Eq. (23), shown by the line in Fig. 13, gives a value $C_2 = 1.91 \pm 0.11$, and a least-squares fit to the data in module 104 alone gives a value $C_2 = 1.94 \pm 0.11$. Thus, both the central densities and the densities at $|x| \geq 4\text{ }\mu\text{m}$ in module 104 have average values that are indistinguishable from the overall averages. The standard deviation in C_2 corresponds to an ability to determine Z/β of an unknown particle with a fractional error of about 4%.

We believe that these results for Fe tracks, together with the results for core radii in Fig. 10, constitute strong evidence that the abnormally low density of silver grains for the monopole candidate is due to a property of the particle and not to a low sensitivity of that emulsion relative to the other emulsions.

D. Photomicrographic evidence

The abnormally low density of silver grains around the monopole-candidate track is quite easily seen in a microscope by even an inexperienced observer and is quite obvious in a photomicrograph. From the complete sample of ultraheavy cosmic-ray tracks we selected those with zenith angles nearly the same as that of the monopole candidate ($\theta = 10^\circ$), so that the effects of ob-

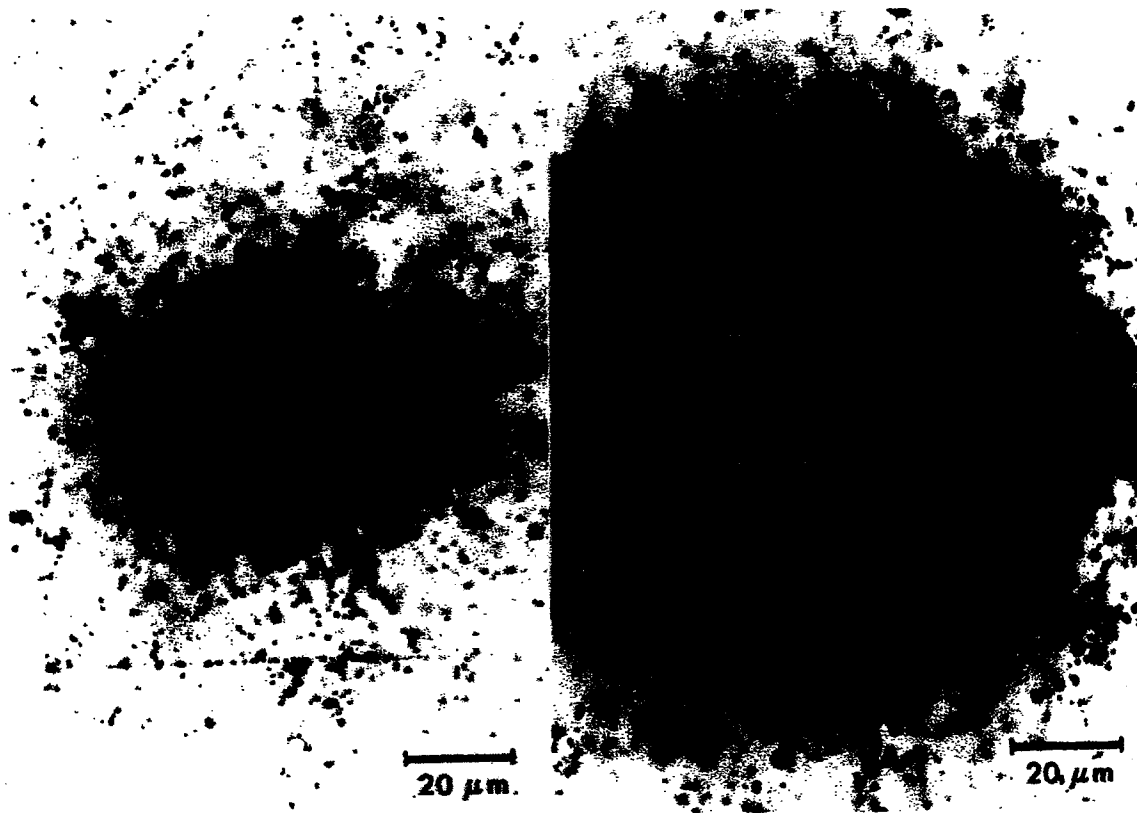


FIG. 14. Photomicrographs in G-5 emulsion of (a) the monopole-candidate track, with $Z/\beta = 114$ and zenith angle $\theta = 10^\circ$, and (b) the track of a nucleus with $Z = 75$, $\beta = 0.67$, $Z/\beta = 112$, and $\theta = 14^\circ$. For both tracks the region in focus is about one-third of the way below the top surface of the emulsion.

scuration by out-of-focus grains and transition effects at the surfaces would be comparable. The photomicrographs in both Figs. 14 and 15 were taken at equal magnifications, about $\frac{1}{3}$ of the way down each track. A $53\times$ oil objective with a high numerical aperture (0.95) was used, which means that only grains within a micron or so of the focal plane are in focus. Figure 14 compares the silver grain distributions around the tracks of the monopole candidate and of a nucleus with $Z = 75$, $\beta = 0.67$, $Z/\beta = 112$, and $\theta = 14^\circ$. It is fortunate that this event with almost identical Z/β and θ to those of the monopole candidate occurred on the Sioux City flight. The eye can readily see that over a wide range of distances outside the core the distant energy deposition is much lower for the monopole candidate than for a normal nucleus with $Z/\beta = 112$. The striking difference between the two particles is clear in each of the 40 pairs of micrographs taken at different depths from top to bottom of the emulsion. The large central dark region, which consists of grains in the optical path but not necessarily in focus, obscures the

smaller core region in these photographs. The cores of saturated darkening can only be seen by direct microscopic examination. Their radii are about the same, $\sim 6 \mu\text{m}$, as seen in Fig. 10. We reiterate that the distortion of the monopole-candidate track caused by intensive optical examination occurred after these photographs were made.

Figure 15 compares these two tracks with all other steep tracks having $8^\circ \leq \theta \leq 14^\circ$, $Z/\beta > 70$, and $Z > 40$. The values of Z , β , and θ for the nine events are given in Table III. The values of Z/β are labeled in the figure. The micrographs are arranged in a sequence of increasing size of the region of intense darkening, going from top to bottom and from left to right. Note that with two exceptions the size of the dark region, a rough measure of the density of silver grains at radial distances ~ 15 to $\sim 40 \mu\text{m}$, increases with Z/β . The first exception is the monopole candidate, whose photograph looks similar to that for a normal fast nucleus with $Z/\beta \approx 80$. The second exception is the very slow event in the upper right, which has $Z/\beta = 120$ but has a dark region smaller than that for

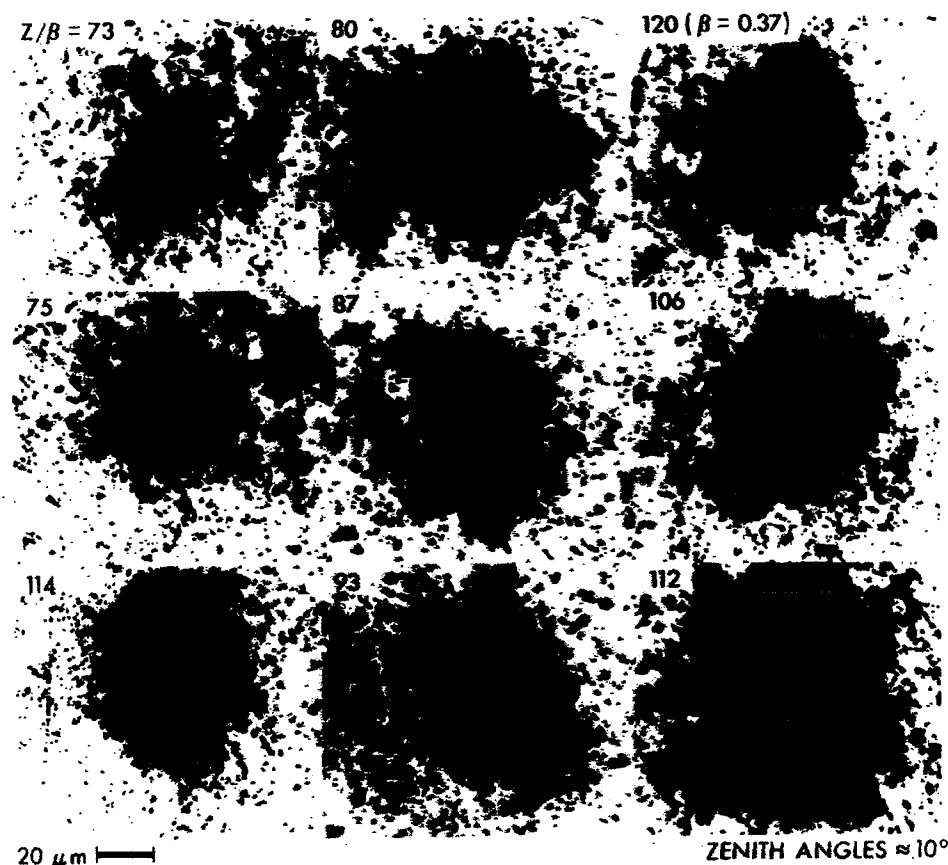


FIG. 15. Photomicrographs of tracks of the events in Table II, which have similar zenith angles and values of Z/β ranging from 73 to 120. The abnormally small density of silver grains for the monopole-candidate track is obvious.

the fast nucleus with $Z/\beta=106$. The small size of the dark region is a result of kinematics, which cuts off the knockon-electron spectrum at a maximum energy of ~ 160 keV for a nucleus with $\beta=0.37$.

The photomicrographs show clearly that far

TABLE III. Events shown in the micrographs in Fig. 16.

Event number ^a	Zenith angle	Z	β	Z/β
173-102	9°	69	0.95	73
99-3	8°	52	0.69	75
104-121	10°	?	?	114
191-1	11°	53	0.66	80
156-113	9°	83	0.95	87
121-4	10°	56	0.60	93
83-11	11°	44	0.37	120
119-1	13°	57	0.54	106
76-1	14°	75	0.67	112

^aThe first number is the module number.

fewer silver grains were produced around the monopole-candidate track than around the track of event 76-1, the fast nucleus with $Z/\beta=112$. In the absence of a large set of micrographs of tracks of nuclei with all possible combinations of Z and β giving $Z/\beta=114$, we have to utilize models of track structure to predict how the grain density will vary with Z and β and how fluctuations in the energy deposition can affect track structure. We will do this in Sec. VIIA. We point out explicitly here that the difference in grain densities in Figs. 14(a) and 14(b) cannot be attributed to an abnormality in event 76-1. The emulsion in module 76 had a sensitivity indistinguishable from the sensitivity of the emulsion in module 104. Moreover, there were several other events in the flight with $Z/\beta>112$ and higher silver grain densities which we did not show in photographs because of the difficulty of making visual comparisons of tracks with quite different zenith angles. To show that event 76-1 did not have an abnormally high grain density, in Fig. 16 we compare that event with



FIG. 16. Other tracks at zenith angles similar to those in Fig. 15. In the left column are tracks of particles with Z/β between 79 and 87; in the middle column the Z/β is between 112 and 118; in the right column Z/β is greater than 125.

others of lesser, comparable, and greater values of Z/β and zenith angles between 8° and 14° . Event 76-1 appears at the top of the middle column. Our events 156-113 and 191-1 are at the middle and bottom of the first column. The other six events are from emulsion exposed by the Bristol and Dublin groups.¹⁰ All nine photomicrographs were taken under identical conditions in Fowler's laboratory. The events in the first column have Z/β between 79 and 87 and are similar in appearance to event 104-121, our monopole candidate. The events in the second column have Z/β between 112 and 118 and are illustrative of the appearance the track of event 104-121 should have if it were a normal ($Z \leq 96$) fast nucleus with $Z/\beta = 114$. The events in the third column have $Z/\beta \geq 125$ and are illustrative of steep tracks with considerably higher silver grain density than the track of event 76-1. Even though, because of their different histories, the tracks in the Bristol/Dublin emulsions should not be compared quantitatively with the tracks in our emulsions, the qualitative trends in growth of silver grain content of tracks in all

the emulsions are similar and support the contention that event 76-1 was not at the extreme upper end of the distribution of track sizes for ultra-heavy cosmic rays.

E. Quantitative studies of the Kodak NTB-3 emulsions with AMID

The two layers of 10- μ m Kodak NTB-3 emulsion, each coated on a 200- μ m-thick cellulose triacetate base and independently wrapped in opaque paper, provide independent evidence for the deficiency of silver grains around the monopole-candidate track. The appearance of tracks in thin emulsion is quite different from that of tracks in Ilford 200- μ m emulsion. The thin emulsion can be thought of in first approximation as an infinitesimally thin detector of energetic electrons generated in the low- Z material above and below it by the ultraheavy cosmic ray. Fewer knockon electrons per unit volume are produced in the low- Z material than in the emulsion. Those that are produced do not scatter as frequently as they would in emulsion; they stream to a greater radial

distance before reaching the end of their range. The silver grain density is lower and individual δ rays can be more readily recognized and followed than in thick emulsion.

After development the Kodak emulsion is only $\sim 6 \mu\text{m}$ thick, and the number of silver grains per event is small. Considerable effort is required to find each event with an optical microscope, but once an event is located, the silver grain distribution can be quite readily determined with the AMID system developed at Houston. For events 76-1 and 104-121, we etched the plastic backing of the thin emulsions and confirmed that the events had been correctly located. For the other events, we found several Fe tracks near each ultraheavy event that could be traced through the thin and thick emulsions and that confirmed the correctness of the location. All events with $\theta < 20^\circ$ and $Z/\beta \geq 80$ in both sets of thin emulsions were selected for measurements. In addition, we selected 104-117, with $\theta = 0^\circ$ and $Z/\beta = 66$, because it was within 8 cm of event 104-121, and we selected a random sample of four additional events with $\theta < 20^\circ$ and $60 < Z/\beta < 80$ to extend coverage over a wide range of values of Z/β . An event is first centered on the microscope stage and focused by hand at a particular depth in the emulsion. An image dissector divides the image into cells of size $0.25 \mu\text{m} \times 0.25 \mu\text{m}$ and an integral minicomputer determines whether each cell is or is not within a developed silver blob. The blob recognition algorithm yields results independent of absolute illumination level over a wide range, and variation of integration time to achieve constant total signal for each cell ensures a constant signal-to-noise ratio. The total number of cells within blobs is thus a measure of the amount of developed silver within the focal depth for that particular field of view.

After one scan is complete the operator focuses the stage at a different depth and starts a new scan. For the thin emulsions essentially all of the silver blobs could be recorded with scans at only two vertical positions of the stage. A computer program sums the filled cells at a given radial distance, subtracts a background reading, and generates a quantity proportional to silver density above background as a function of radial distance from the trajectory. For the thin emulsions we defined the background density as the average density of filled cells in an annulus from 40 to 80 μm . The total number of silver blobs per event in the thin emulsions is too low to warrant using the radial distributions, but provides quite significant information when we sum the signal cells within a cylinder of radius 30 μm centered on the track.

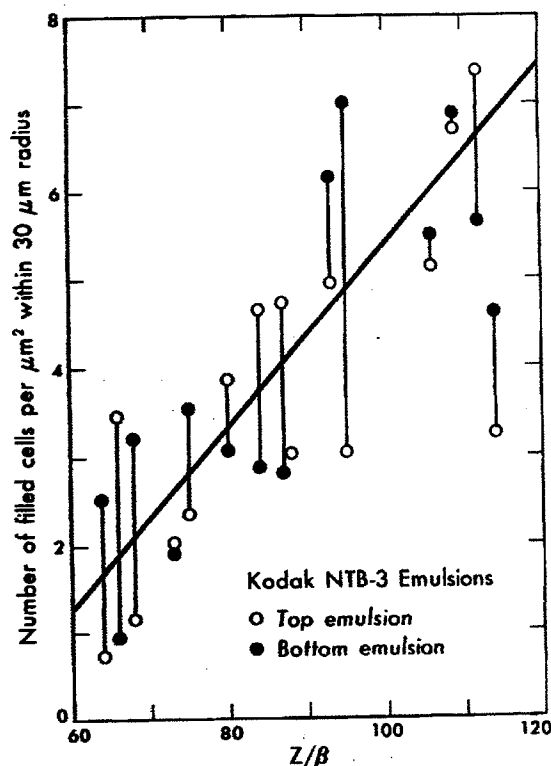


FIG. 17. Density of silver blobs in a cylinder of 30- μm radius around the track in thin emulsion as a function of Z/β for tracks with $\theta \leq 18^\circ$. Reproducibility of measurement at each point is better than the size of the point. In both emulsions the silver grain density for the monopole candidate (at $Z/\beta = 114$ on the graph) is much lower than expected from the least-squares line for normal nuclei.

Figure 17 shows the density of filled cells within a circle of radius 30 μm , after background subtraction, as a function of Z/β . Data for the upper and lower Kodak emulsions are indicated by open and closed circles, respectively. Repeated measurements on the same tracks have shown that the standard deviation of the measurements is 2%. One open circle in Fig. 17 has no corresponding closed circle; the track in that emulsion was obscured by a general blackening due to a mechanical deformation of that region. The important result of these measurements is that for both emulsions the point for the monopole candidate lies well below a least-squares line through the remainder of the data.

Assuming no systematic errors and a normal distribution of errors due to the statistics of δ -ray production and of grain development in the thin emulsion, we can assess the significance of the departure of the measurements for the monopole

candidate from the value expected for a normal nucleus. Let S_{30} denote the density of filled cells within the circle of 30- μ m radius. Because the δ rays contributing to S_{30} are produced and are scattered both in the thin emulsion and in the surrounding low- Z medium, the dependence of S_{30} on Z/β may be more complicated than it would be for the thick emulsion. For convenience we have calculated errors and confidence levels assuming a linear and a quadratic dependence on Z/β . On the assumption $S_{30} = a + b(Z/\beta)$, the measured values of S_{30} for the monopole candidate in the top and bottom emulsions lie 3.38σ and 2.07σ below the least-squares line in Fig. 17, and the product of the confidence levels for the two measurements to be part of a normal distribution about the line is 7.1×10^{-6} . If S_{30} is assumed to vary as $S_{30} = a + b(Z/\beta)^2$, then the product of confidence levels for the two points is 2.9×10^{-6} . For either a linear or quadratic dependence on Z/β , the thin emulsions provide strong supporting evidence for an abnormally small density of energy deposited by the monopole candidate in close collisions. From an examination of photomicrographs of the tracks in the thin emulsions, we believe that the large fluctuations of the values of S_{30} in Fig. 17 are entirely consistent with the statistics of a thin detector having a limited number of developable silver grains.

Some words of caution are in order. This is the first time that Kodak's thin emulsion has been used in a quantitative study of highly charged particles, and our experience with its response is rather limited. Because of the small total number of silver grains produced per particle, it was not feasible for us to calibrate the sensitivity of individual emulsions by measurements of Fe tracks, as we did with the Ilford G-5 emulsions. The points in Fig. 17 may not be normally distributed, in which case our estimate of a confidence level less than 10^{-5} for both points to be part of the same population would be invalid.

Projecting the points for the monopole candidate sideways to the least-squares line, we see that in the top emulsion its silver grain density was like that of a particle with $Z/\beta \approx 80$ and in the bottom emulsion its silver grain density was like that of a particle with $Z/\beta \approx 94$. These results are consistent with the photographic evidence and the visual measurements of R_2 for the 200- μ m emulsion.

Measurements of the radial distribution of silver blobs around tracks in the 200- μ m emulsions with the AMID system are more laborious than measurements in the thin emulsions because of the much greater information content. Considerable progress has been made with these measurements,

and it is now clear that they support the visual and photographic evidence to the effect that the monopole candidate has a track structure similar to that for an ordinary nucleus with $Z/\beta \approx 90$ and $0.6 \leq \beta \leq 0.95$, but grossly different from that for an ordinary nucleus with $Z/\beta = 114$, $Z \leq 96$, and $\beta \geq 0.6$. These measurements, after correction for distortion, may make it possible to eliminate some of the now acceptable interpretations. When completed, these results will be reported in a detailed paper on measurements and calculations of track structure.

VII. PARTICLES COMPATIBLE WITH BOTH THE LEXAN DATA AND THE EMULSION DATA

A. Track-structure calculations

Some important qualitative features of track structure can be inferred from Fig. 18, which shows the ratio of the exact Mott cross section³⁵ to the Rutherford cross section for the process in which an electron at rest in emulsion is scattered by a nucleus or antinucleus with $|Z|/\beta = 114$. The abscissa gives the lab kinetic energy, as well as the true range, of the scattered electron. (Because of multiple Coulomb scattering, the radial distance diffused from the trajectory of the incoming particle will be much smaller than the electron range.) For tracks in Lexan the relevant electron energies are less than ~ 1 keV; for the saturated core in emulsion (R_1), the electron energies are ~ 1 to ~ 50 keV; and for the halo (R_2) or photographically detectable region of darkening

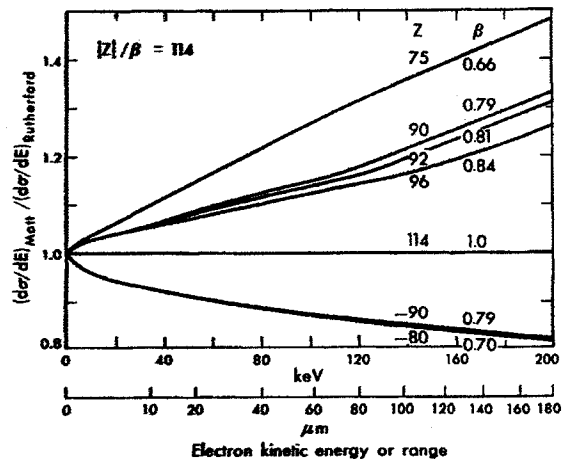


FIG. 18. Ratio of exact Mott cross section to Rutherford cross section as a function of kinetic energy or range for an electron initially at rest to be scattered by a fast nucleus or antinucleus with $|Z|/\beta = 114$. Radial-diffusion distance of an electron from a track in emulsion is much smaller than the range.

in emulsion, the electron energies are ~25 to ~1000 keV. One sees from the figure that the cross-section ratios for producing electrons with energies ~50 to a few hundred keV are smallest for an antinucleus, intermediate for an ultrarelativistic superheavy nucleus, and greatest for long-lived nuclei with $Z \approx 75$ to 96.

We now want to utilize noncontroversial features common to all models of track structure to account for the following two facts: (1) The particle had an average value of $|Z|/\beta$ that did not substantially change from ~114 in passing through ~1.4 g/cm² Lexan equivalent; and (2) it produced energetic knockon electrons at a rate similar to that of a fast normal nucleus with $|Z|/\beta \approx 85$.

We begin by assuming that the silver grain density at a particular radial distance r from a track in emulsion is a measure of the energy per unit volume deposited by δ rays at that point. A linear relationship is reasonable at radial distances ($r \geq 10 \mu\text{m}$) where the proportion of grains developed is low enough that individual grains can be counted. We are thus interested in an expression for $\epsilon_e(r)$, the energy deposited per unit volume at radial distance r from a short segment of track in an emulsion of finite thickness $t \approx 200 \mu\text{m}$, sandwiched between plastic or paper of low Z .

Let us first discuss the case of an infinitely thick emulsion considered by Fowler and by Osborne. To find $\epsilon_e(r)$ we need an expression for the energy spectrum of knockon electrons produced per unit length of track segment and a way of accounting for the spatial dependence of the rate of energy loss of the electrons as they undergo multiple Coulomb scattering and straggling from their most probable range. It is useful pedagogically to outline Fowler's model because it leads to a simple analytic expression for $\epsilon_e(r)$. (Several aspects of this model are wrong in detail, but it reproduces quite well many of the features of energy transport by the δ rays.) In order to arrive at an integrable expression, Fowler¹⁶ uses the simple Rutherford scattering cross section which leads to the expression for the number of δ rays per cm

$$dN \approx 2\pi N_e Z^2 r_e^2 \frac{m_e c^2}{\beta^2} \frac{dw}{w^2} \quad (\text{cm}^{-1}) \quad (24)$$

for

$$w < w_{\text{max}} = 2m_e c^2 \beta^2 \gamma^2. \quad (25)$$

N_e is the number of electrons/cm³ in the emulsion and $r_e = e^2/m_e c^2$. Fowler then assumes that, independent of initial direction, multiple Coulomb scattering is so intense that electrons of energy w emitted from a line source diffuse isotropically,

$$\frac{dP(r)}{dw} = \frac{wdN/dw}{2\pi\sigma^2(w)} \exp\left[-\frac{r^2}{2\sigma^2(w)}\right] \quad (\text{erg cm}^{-3}) \quad (26)$$

with a diffusion distance $\sigma(w) \approx 0.22 R(w)$, where the true range $R(w)$ is approximated by a power-law relation

$$R(w) = kw^n, \quad n \approx 1.54. \quad (27)$$

He finds that the energy deposited in a thin cylindrical shell is given approximately by

$$dE/dr = w R^{-1} f(r/R) \quad (28)$$

with $f(r/R)$ independent of w . Integrating along the track and over the knockon spectrum [Eq. (24)], he obtains the simple expression

$$\epsilon_e(r) \approx \frac{2.2Z^2}{\beta^2 r^2} \exp\left(-\frac{r^2}{2\sigma_{\text{max}}^2}\right) \quad (\text{eV}/\mu\text{m}^3), \quad (29)$$

where $\sigma_{\text{max}} = 0.22 R_{\text{max}}$.

Consider now the dependence of ϵ_e on β for particles with fixed Z/β . We must consider the behavior of the exponential factor for values of r less than ~100 μm where the density of silver grains is still large enough to measure. For $r < 100 \mu\text{m}$ and large diffusion distance, corresponding to a large kinematic cutoff and large β , the exponential factor is essentially unity and $\epsilon_e(r)$ does not depend on β for particles with fixed Z/β . The thin-down regime where the depletion of silver grains becomes detectable corresponds to a β small enough that $r \geq 0.3R_{\text{max}}$. Both this simple analytic model and the experience of Fowler and co-workers⁴² indicate that $\beta \approx 0.45$ is the practical limit above which one cannot conclusively determine the velocity of an ultraheavy cosmic ray by photodensitometric measurements.

Among the defects of the model, the most serious are the failure to use the exact Mott cross section and neglect of the initial direction of the emitted electrons. Failure to use the Mott cross section (which would necessitate numerical integration) means that (1) the model does not distinguish nuclei from their conjugate antinuclei, (2) the cross section is seriously underestimated in many cases for ordinary nuclei, and (3) the decrease in cross section for $Z/\beta \geq 100$ as β increases toward 1 is not described. Neglect of the initial direction of the emitted electrons led to the simple conclusion that the only difference in ϵ_e for different values of β is caused by δ rays with energies between w_{max} for one β and w_{max} for another β . Naturally as $\beta \rightarrow 1$ these differences vanish. However, it is well known that the dependence of the initial direction of an electron on its energy w and on β of the particle can have an important effect on ϵ_e . The lab angle θ_{lab} of

emission of an electron of energy w is given by

$$\theta_{1ab}(w) = \arctan \left[\frac{2m_e(w_{\max} - w)}{w(w_{\max} + 2m_e)} \right]^{1/2} \quad (30)$$

when we neglect initial binding of the electron.

On the average, a δ -ray path is roughly straight for about the first 25% of its range, so that a δ ray is transported to $r \approx 0.25 R \sin \theta_{1ab}$ away from the particle's trajectory before it becomes "randomized." At fixed Z/β , as β increases, the δ rays of any fixed energy $w_0 \leq w_{\max}(\beta)$ are ejected at steadily increasing angles, which leads to a systematic increase of ϵ_p at large r that is not taken into account in Eq. (29). Inclusion of this effect should increase somewhat the range of velocities that can be detected by measurements of $\epsilon_p(r)$.

Application of Fowler's model to the behavior of $\epsilon_p(r)$ for low velocities leads to the conclusion that $\epsilon_p(r)$ for a particle with $Z/\beta = +114$ and $\beta \approx 0.4$ will be similar, at $20 \leq r \leq 40 \mu\text{m}$, to $\epsilon_p(r)$ for a fast nucleus with $Z/\beta = +85$, $\beta > 0.6$. Fowler's model cannot be used to compare quantitatively the track structure of various fast particles with $|Z|/\beta = 114$ because of his failure to use the Mott cross section. (In their analysis of tracks of ultraheavy cosmic rays in emulsion, Fowler *et al.*¹⁶ measured the optical density at a fixed distance from the track core and crudely corrected the model by multiplying the value of ϵ_p at the fixed distance by the ratio of the Mott cross section to the Rutherford cross section for electrons of some average energy believed to be most effective at that fixed distance.)

Osborne's model is an extension of the track-structure model of Katz and Kobetich²⁷ and their electron-energy-deposition algorithm.³⁸ His expression for the energy spectrum of knockon electrons produced per unit length of track segment differs from Eq. (24) in that he uses the Mott cross section instead of the Rutherford cross section. His computer program that calculates $\epsilon_p(r)$ as a function of r , Z , and β contains a table of Mott cross sections calculated by Spencer⁴³ for values of Z from -110 to $+110$, for β from 0.2 to 0.99 , and for center-of-momentum scattering angles θ from 0 to 180° . The relation between θ , w , and w_{\max} is simply

$$w = w_{\max} \sin^2(\frac{1}{2}\theta). \quad (31)$$

Osborne follows the Kobetich and Katz approximate treatment of electron energy transport.³⁸ He has taken two approaches with respect to $\theta_{1ab}(w)$, the angular distribution of electrons. The first approach uses the value of θ_{1ab} given by kinematics and overestimates the effect of initial direction of the electrons. The second approach uses $\theta_{1ab} = \pi/2$ for all electron energies and ignores the effect of

initial directions. The real situation should lie between these extremes. Although the problem has cylindrical symmetry, Kobetich and Katz make a one-dimensional approximation that enables them to use an algorithm for electron energy dissipation fitted to experimental data and to the calculations of Spencer⁴⁴ for monoenergetic electrons normally incident on flat slabs. They assume that the energy dissipation at radial distance r of electrons ejected at angle θ_{1ab} is equal to the energy dissipation of these electrons normally incident on a slab of thickness $t = r/\sin \theta_{1ab}$, and that the effect of electrons that scatter so as to interact with too little material compared to a slab is compensated by those that encounter too much material. They express the energy density on the cylinder in terms of the energy flux through the cylinder, F ,

$$\epsilon_p(r) = -(2\pi r)^{-1} dF/dr, \quad (32)$$

and write dF/dr as

$$dF/dr = \int_{w_1-I}^{w_2-I} \frac{d}{dt} \left(W(r, w-I, \theta_{1ab}) \eta(r, w-I, \theta_{1ab}) \frac{dN}{dw} \right) \times dw, \quad (33)$$

where $w_1 - I$ and $w_2 - I$ are the kinetic energies of δ rays that just reach the cylinder of radius $r = t \sin \theta_{1ab}$. I is an average ionization potential for emulsion, dN/dw is the δ -ray energy spectrum given by the Mott cross section, W is the residual kinetic energy of an electron of initial kinetic energy $w - I$ that penetrates a slab of thickness t , and η is the probability of transmission through the slab. The reader is referred to Refs. 37-39 for the details of the calculation of ϵ_p for the simple case in which dN/dw is given by Eq. (24).

Osborne's model, with its use of the Mott cross section, correctly predicts large differences in $\epsilon_p(r)$ for nuclei and antinuclei with the same $|Z|/\beta$. Like Fowler's model, Osborne's model predicts that for a fixed $|Z|/\beta$ the major changes in $\epsilon_p(r)$ at $r < 100 \mu\text{m}$ will occur for small β . However, in Osborne's model changes in $\epsilon_p(r)$ can be seen for large Z/β (≥ 100) as β increases from 0.9 to 1.0 , and changes in $\epsilon_p(r)$ in the low-velocity regime can still be seen at β up to roughly 0.6 . The changes in the high-velocity regime occur because the effective cross section must decrease to the Rutherford cross section as β approaches unity. Both models predict, for large β , that $\epsilon_p(r)$ decreases approximately as r^{-2} .

In Osborne's model three classes of hypothetical particles could have energy deposition rates ϵ_p similar to that of a fast nucleus with $Z/\beta \approx 85$ to 95 at radial distances $20 \leq r \leq 40 \mu\text{m}$: an extremely relativistic ($\beta \geq 0.99$) superheavy nucleus ($Z \approx 114$), a fast antinucleus with $Z/\beta \approx -114$, and a slow par-

ticle with $Z/\beta \approx +114$ and $\beta \approx 0.45$ to 0.5. With θ_{lab} given by kinematics, the ratio of ϵ_p for particles with $Z/\beta = +114$ to ϵ_p for a fast nucleus with $Z/\beta = +85$ increases as β increases until it reaches a maximum at $\beta \approx 0.85$ and then decreases as β approaches 1. At $r = 30 \mu\text{m}$ the ratio is ~ 2 for values of β between 0.6 and 0.84, corresponding to nuclei up to $Z = 96$, whereas for $\beta \geq 0.99$ the ratio is 1.25. For a hypothetical nucleus with $Z/\beta = +110$ and $\beta \geq 0.99$, which will be of interest to us in later sections, the ratio is only 1.13. With θ_{lab} fixed at $\pi/2$, the ratio is ~ 1.85 for $Z/\beta = +114$ and $0.6 \leq \beta \leq 0.84$ and drops to 1.40 for $\beta \geq 0.99$. For $Z/\beta = +110$ and $\beta \geq 0.99$ the ratio is ~ 1.30 . For either choice of θ_{lab} , Osborne's model shows that the track structure for an ultrarelativistic superheavy nucleus, $Z \approx 110$ to 114, is significantly smaller than that for $Z/\beta = +114$ and $0.6 \leq \beta \leq 0.84$ and close to that for $Z/\beta = +85$.

In principle, Hagstrom's model¹⁴ overcomes the drawbacks of Fowler's and Osborne's models. It was designed to describe both expectations and fluctuations in energy deposition in emulsion. Hagstrom used a Monte Carlo program to calculate $\epsilon_p(r)$ for a track segment perpendicular to an emulsion of thickness $200 \mu\text{m}$ surrounded by a vacuum. For our event, with zenith angle $\sim 10^\circ$, this is a good approximation; the calculation is easily extended to arbitrary zenith angle. He used a table of Mott cross sections for particles with $-110 \leq Z \leq +110$, $0.2 \leq \beta \leq 0.99$, and center-of-mass scattering angles $0^\circ \leq \theta \leq 180^\circ$. To keep the duration of the calculation for an individual event at a reasonable level, he followed the production of primary electrons only of energies greater than 25 keV. A 25-keV electron travels a radial distance no more than $\sim 5 \mu\text{m}$ from the particle's trajectory. The omission of electrons with $w \leq 25$ keV thus invalidates the calculation only in the core region of the track. For each trial particle of a given Z and β the Monte Carlo program generated a spectrum of primary knockon electrons with $w \geq 25$ keV along a line of length equal to the thickness of the emulsion before development ($200 \mu\text{m}$). Each primary electron was followed as it scattered and transferred energy to bound electrons in the medium. All collisions were treated rigorously, using exact forms both for the multiple small-angle scatters and the large-angle scatters and taking shielding into account. The Berger-Selzer range-energy relation for electrons was used,⁴⁵ and range-straggling of the electrons was included. An electron that reached the surface of the emulsion was considered to be lost. (The probability of being back-scattered into the emulsion from the low- Z plastic or paper in contact with the emulsion was taken to be zero.) The emulsion was described

as a mixture, not as a single element. Granularity was ignored; this is quite a safe approximation at radial distances greater than $\sim 1 \mu\text{m}$. The model contains no fitting parameters.

Hagstrom found that his model reproduces remarkably well the shapes and absolute magnitudes of the appropriate calculations of Spencer⁴⁴ for point isotropic and plane perpendicular sources of monoenergetic electrons.

Hagstrom has published a summary of some of his findings¹⁴ and has supplied us with numerous graphs of $\epsilon_p(r)$ for various combinations of Z and β . Because he has not published his study, we restrict ourselves to qualitative statements about his findings regarding energy deposition by particles with $|Z|/\beta \approx 114$ in the $200\text{-}\mu\text{m}$ emulsion at radial distances $10 \leq r \leq 50 \mu\text{m}$ where good measurements of grain density or optical density can be made. Note that his results are not precisely comparable with our emulsion measurements because he summed over the entire $200\text{-}\mu\text{m}$ emulsion thickness, whereas in our visual, photographic, and AMID measurements we ignored the regions near the top and bottom of the emulsion where the transition effects are large.

We make the following inferences from the Monte Carlo calculations:

(1) All positive nuclei with $Z/\beta \approx +114$ and $0.6 \leq \beta \leq 0.95$ have statistically indistinguishable energy deposition curves, $\epsilon_p(r)$, which are decisively higher than the curves for positive nuclei with $Z/\beta = +85$ and $0.6 \leq \beta \leq 0.95$.

(2) The energy-deposition curve for a hypothetical nucleus with $Z/\beta = +110$ and $\beta \geq 0.99$, which will be of interest to us in later sections, is considerably lower than the curves for $Z/\beta \approx +114$ and $0.6 \leq \beta \leq 0.95$. It lies about halfway between the curves for those nuclei and the curves for nuclei with $Z/\beta = +85$ and $0.6 \leq \beta \leq 0.95$.

(3) Antinuclei with $Z/\beta \approx -109$ to -114 and $0.65 \leq \beta \leq 0.85$, which fit the Lexan data, have energy deposition curves at radial distances $20 \leq r \leq 100 \mu\text{m}$ that are quite similar to that for a fast normal nucleus with $Z/\beta = 85$.

(4) A slow particle with $Z/\beta = 114$ and $\beta \approx 0.4$ has an energy deposition curve that is steeper than the curve for the nucleus with $Z/\beta = 85$ but has a similar magnitude at intermediate radial distances, ~ 20 to $\sim 40 \mu\text{m}$. It deposits essentially no energy beyond $\sim 50 \mu\text{m}$.

(5) From several hundred Monte Carlo simulations, Hagstrom found that all curves of $\epsilon_p(r)$ for nuclei with $Z/\beta = +114$ and $0.6 \leq \beta \leq 0.95$ lie well above all curves for fast nuclei with $Z/\beta = +85$ and well above all curves for fast antinuclei with $Z/\beta = -114$.

The rigorous approach of Hagstrom is superior